THE EFFECTS OF A MOVING WALL ON THE SECONDARY FLOW IN A CASCADE

F. R. TOLINE
AND
R. H. WATSON
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THE EFFECTS OF A MOVING WALL ON
THE SECONDARY FLOW IN A CASCADE

by

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SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
(1953)

Cambridge, Massachusetts
May 25, 1953

Professor Shatswell Ober, Chairman
Department Committee on Graduate Students
Department of Aeronautical Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In partial fulfillment of the requirements for the degree of Master of Science in Aeronautical Engineering, I herewith submit a thesis entitled "The Effects of a Moving Wall on the Secondary Flow in a Cascade".

Respectfully,

Francis R. Toline

20530

Cambridge, Massachusetts
May 25, 1953

Professor J. P. Den Hartog, Chairman
Department Committee on Graduate Students
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering, I herewith submit a thesis entitled "The Effects of a Moving Wall on the Secondary Flow in a Cascade".

Respectfully,

Robert H. Watson, Jr.

Acknowledgements

The authors wish to express their appreciation to Professor Edward S. Taylor for the valuable suggestions offered throughout the investigation, and to Professor Robert C. Dean for his close personal supervision and guidance.

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THE EFFECTS OF A MOVING WALL ON THE SECONDARY FLOW IN A CASCADE

by

F. R. Toline

and

R. H. Watson

(Submitted to the Department of Aeronautical Engineering and to the Department of Mechanical Engineering on May 25, 1953, in partial fulfillment of the requirements for the degree of Master of Science.)

ABSTRACT

In present day design of turbomachinery, the understanding of the nature and the influence of secondary flow is of great importance. The difficulties encountered in the mathematical theory of the three-dimensional flow in turbomachinery has led to studies of the flow by visualization techniques using smoke, and by measurement of velocity pressures and flow angles in two-dimensional cascades in order to obtain information that might be used in the design of such machinery.

This investigation was concerned with the study of the effects of relative motion between blades and wall in a compressor cascade using velocity pressure and flow angle measurements. The moving wall affected the secondary flow by displacing the flow in the direction of motion of the moving wall. The losses with a moving wall were confined to a region nearer to the wall than in the case of no relative motion between blades and wall.

The flow in the boundary layer with no end clearance (stator row) overturns, producing a larger angle of attack on the following rotor row than designed. The flow in the boundary layer with moving wall (compressor rotor row) underturns and makes a smaller angle of attack with the next stator row than the designed angle.

All data taken were very reproducible. The accuracy of all readings taken in regions of small velocity gradient and small pitch angles is approximately plus or minus 0.1 degree for yaw and pitch angles, and plus or minus 0.4 percent for stagnation pressure. In regions of low stagnation pressure and high velocity gradient the accuracy of readings is approximately plus or minus 0.5 degrees in yaw and pitch angles and plus or minus 1.0 percent in stagnation pressure. Due to the method of measuring pitch, any pitch angle greater than about 15 degrees is not accurate and only serves to indicate an order of magnitude.

Thesis Supervisor: Robert C. Dean, Jr.

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INTRODUCTION

In the design of turbomachinery and in the analysis of their performance it is important that there be an understanding of the nature and influence of secondary flow. Theories of turbomachines based on wind tunnel or two-dimensional flow represent an approximation of the actual flow. The flow in turbomachinery is three dimensional and presents difficulties in the mathematical theory. Deviations from the flow behavior, as predicted by potential flow analyses are termed secondary flows. Various theoretical and experimental investigations have been made which partially describe the manner in which secondary flows affect the performance of turbomachines.

The effects of end clearance and relative motion between the blade and wall were investigated by Hertzig, Hansen and Costello (Refs. 1 and 2). This work was done using smoke visualization techniques as described in Ref. 1. A low speed two-dimensional cascade and a high speed three-dimensional cascade were used in the investigation described in Ref. 1. A further investigation by the NACA (Ref. 3), in which visualization techniques were again used, dealt with the effects of tip clearance and relative motion between blade and wall with high-turning blades. An investigation at the Massachusetts Institute of Technology Gas Turbine Laboratory by Van Le (Ref. 4) concerned the effect of boundary layer on secondary flow. This work was conducted in a low speed tunnel using a compressor cascade.

It was proposed to investigate tip clearance and moving

wall effects on secondary flows as a continuation of the work done by Van Le. The work was undertaken after improvements in the instrumentation and a redesign of compressor cascade blading.

RESULTS AND DISCUSSION

Four runs were made with a constant value of inlet velocity of the order of 120 feet per second but with varying cascade conditions. The runs made and the conditions during each one were as follows:

Run No. 1 -- No end clearance.

Run No. 2 -- 5/16" end clearance.

Run No. 3 -- 1/8" end clearance.

Run No. 4 -- 1/8" end clearance with moving wall.

The results obtained are shown in Figures 7 through 18 as contour maps there being a separate map for percentage of stagnation or total pressure, yaw angle and pitch angle respectively for each run. The contours all terminate at Z equal to 0.13 inches from the wall, since it was impossible to obtain readings any closer to the wall with the probe used. In runs with end clearance, the ends of the blades are indicated by a dashed horizontal line.

Due to the three-dimensional nature of the flow, it is necessary when visualizing the flow to use all three contours for a particular run for example, the yaw angle and pitch angle at a point to determine the direction of a velocity vector and the percent of stagnation pressure to determine the length of the vector. Another fact which must be remembered when viewing the maps is that the equation of continuity which must be satisfied in the three-dimensional flow does not necessarily have to be satisfied in the two-dimensional plane of the flow

which the maps represent. In addition one should bear in mind when analysing any of these maps the shape and thickness of the boundary layer ahead of the cascade as shown in Fig. 6.

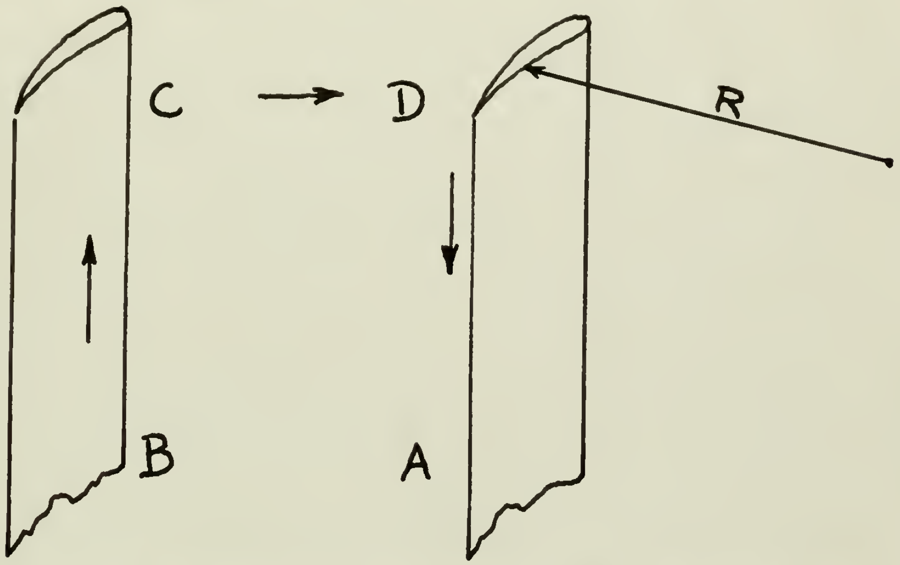
All runs were made in a plane 1/2 chord length downstream of the trailing edges of the cascade blades (plane B). Therefore, it is necessary to realize that the flow in this plane is the result of disturbances and forces at work in the blade passage. The previous results of Van Le, and of Hertzig, Hansen, and Costello were used rather extensively in analysing the results in plane B to determine the forces in the cascade which produced these results.

Considering Run No. 1, with no end clearance, the results were as expected from previous investigations by Van Le under the same conditions. Fig. 7 shows that the region of high stagnation pressure has been distorted so that it is extending upward along the pressure surface of the blade, while the region of low energy fluid near the wall has been displaced toward the suction side of the blade. This movement is also apparent from the contours of yaw and pitch angles, and the overall flow picture obtained is that of a large scale "passage rotation" of all the fluid toward the suction surface at the blade tips. The approximate center of this rotation was about 1/3 inch from the wall and about 1 inch from the suction surface.

One fact easily discernible from Fig. 8 is the well-known phenomenon of overturning of the flow in the boundary layer. Over a considerable area between the blades and very near the

wall the yaw angle is minus, indicating overturning of the flow while the region of underturning near the wall is confined to small areas in the blade wake.

The overturning of the flow in the boundary layer and the large scale "passage rotation" is easily understood by considering the sketch below.



In order to balance the centrifugal forces caused by the turning of the flow in passing through the cascade, there is a pressure gradient from A to B at midspan according to $\frac{dp}{dR} = \frac{\rho V^2}{R}$ where R is the radius of curvature of the stream lines. Thus there exists the inequality $p_B > p_A$. By the same reasoning $p_C > p_D$.

Due to the lower velocity in the boundary layer however the stream lines must have a smaller radius of curvature in order to match the midspan pressure gradient. This smaller radius of curvature in the boundary layer accounts for the overturning of the flow.

Even the overturning of the flow in the boundary layer cannot produce a pressure gradient to match that at midspan for in the limiting case at the wall where the velocity is zero, there would have to be a zero radius of curvature. Therefore, the gradient in the boundary layer does not match that at midspan, and the following inequality results:

$$p_B > p_C > p_D > p_A$$

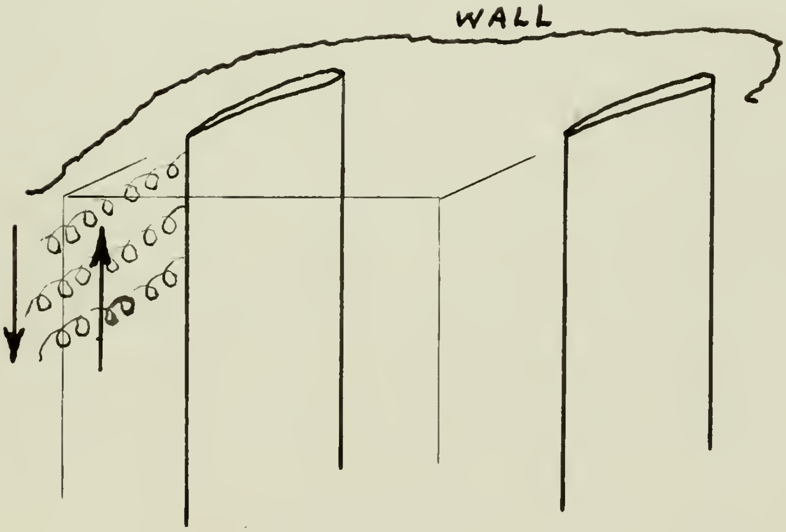
It is this unbalance of forces which produces the large scale "passage rotation".

A close examination of Fig. 7 shows that the blade wake region in the boundary layer has been displaced to the left of the blade wake region in the free stream. An explanation for this is that part of the high energy fluid moving upward along the pressure surface of the blade continues on around in its clockwise rotation toward the suction side of the blade at the tip, while part of it moves toward the pressure side of the blade forcing the low energy fluid of the blade wake to the left and thus causing the distortion of the blade wake region as seen in plane B, 1/2 chord downstream.

One method of analysing the blade wake is to consider the blade wake region as one of shed vorticity. This concept makes use of the fact that the blade may be replaced by a vortex sheet of sufficient strength to satisfy the Kutta condition at the trailing-edge, and in this case, rotating counterclockwise as viewed from above. Then according to the Helmholtz

theorem which says that a vortex filament must end on a solid body or close on itself, and assuming no viscosity, the circulation or vorticity would end abruptly at the wall, and no effects of shed vorticity would be felt downstream. On the other hand, with no friction and any end clearance, the vortex filament would bend at the tip of the blade and continue on downstream undiminished in strength to eventually close on itself at infinity.

The conditions for Run No. 1 were no end clearance, but with viscosity and an entering boundary layer. Since the circulation must vary directly as the entering velocity to satisfy the Kutta condition, the circulation must decrease in the boundary layer, and as the circulation decreases, vortex filaments are shed from the main vortex filament. These shed

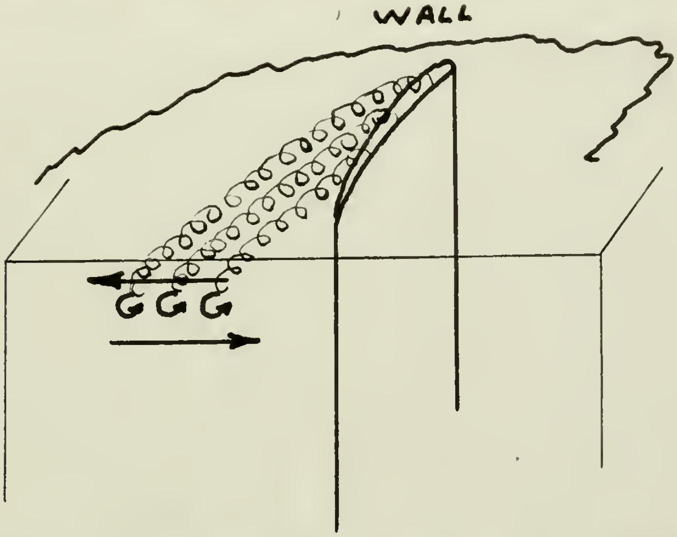


vortex filaments should appear as a vertical vortex sheet in plane B, with the velocity on the left of the sheet downward and on the right upward as shown in the preceding sketch. This expected flow is shown quite clearly by the pitch angle contours of Fig. 9 and extends down from the wall about 1 1/2 inches.

Run No. 2 was made with 5/16 inch or 11.2% chord end clearance and the results are shown in Figures 10, 11 and 12.

The most striking difference between this run and run No. 1 is the large region of low stagnation pressure with a negative region in the center at approximately Y equal to 2.5 and Z equal to 0.5, as shown on Fig. 10. Figure 11 shows a very rapid change in yaw direction in this same region several of the plus and minus yaw contours approaching each other very closely. The flow above the zero yaw line is going to the left or underturning while the flow beneath the zero contour is going to the right or overturning. At first, this would appear to be the vortex filament shed from the tip of the blade. If this were so the counterclockwise rotation of this vortex would produce yaw angles as indicated but in the pitch plane would show up as large minus angles to the left of this region and large positive angles to the right of the region. An examination of Fig. 12 shows that this is not so. The area of large yaw angle change falls in a region of

completely negative pitch. One way of looking at this is to consider the blade replaced by a vortex sheet rather than a single vortex filament. Then the vortex sheet shed from the tip of the blade would produce the effects indicated in the yaw plane of Fig. 11. A sketch of the shed vortex sheet is shown below.



It is obvious from Fig. 11 that the horizontal vortex sheet shed from the tip of the blade is not in line with the blade wake as might be expected. In order for this shed vortex sheet to appear in its displaced location in plane B, it would have to travel downstream from the tip with approximately the direction of the entering stream rather than the average direction of the stream leaving the cascade. No reason is known for the unwillingness of a vortex sheet or filament to turn with the rest of the flow, but the same phenomenon has been observed and photographed by Hertzig, Hansen, and Costello by introducing smoke streams into the flow.

The negative stagnation pressure region in Fig. 10 occurs in

the area of the horizontal vortex sheet shed from the blade tip, i.e., in the region of maximum shear. The only explanation of this negative stagnation pressure area is that the static pressure is all converted to kinetic energy in the velocity of rotation of the vortex sheet, and that this velocity head of the vortex sheet was either not measurable in that particular area or was dissipated by viscous action.

Another obvious difference between the flows of this run and run No. 1 is the absence of the overturning or minus yaw angles in the boundary layer as can be seen in Fig. 11. This is to be expected in the area between the blade tips and the wall where the blades cannot turn the flow. At a location just below where the blade tips would be, in run No. 1, there is still a small amount of overturning. However, in this run, this area of slight overturning is just above the shed vortex sheet, and on the yaw plane, the overturning caused by the boundary layer is completely canceled out by the velocity to the left of the fluid above the shed vortex sheet.

The vertical vortex sheet produced by a gradual shedding of some of the vorticity toward the blade tip due to the gradual decrease of the velocity in the boundary layer is apparent in Fig. 12 as a region in the wake where the pitch angles go from minus to plus when crossing the wake from left to right. The effect is not as strong here as in the first run due to the fact that the area where it occurs is a region of

greater velocity, and because most of the vorticity is shed at the tip of the blade.

It again appears that the large scale "passage rotation" is present, tending to displace low energy fluid toward the suction surface, although its presence is not as apparent as in Run No. 1. The effects of the horizontal vortex sheet shed from the tip of the blade and the flow over the tips of the blades almost completely mask the effect of this "passage rotation", but after a study of all the maps for this run, paying particular attention to the stagnation pressure contours, one explanation of the final result is as follows:

The horizontal vortex sheet shed from the blade tip produces rotation tending to force low energy fluid down along the pressure surface of the blade. In opposition the "passage rotation" and the flow over the tips tends to displace high energy fluid upward along the pressure surface, and these latter forces predominate because of the nearness of the horizontal vortex sheet to the suction surface. The result is that high energy fluid is displaced upward along the pressure pressure surface as may be seen in Fig. 10.

It should be noted that the pitch contours of Fig. 12 which indicate very large negative pitch angles are not exact. Due to the method of obtaining pitch angles, an angle over about 15 degrees is not reliable and only serves to indicate an order of magnitude.

Run No. 3 was made with 1/8 inch or 4.3% chord end clearance. The results are shown in Figures 13, 14, and 15, and are in general the same as those of Run No. 2, except that in this run all the effects are less pronounced due to the smaller amount of end clearance.

No negative stagnation pressure regions were found as in run No. 2. However, as in run No. 2 the region of lowest stagnation pressure coincides with the region of greatest shear in the yaw plane, and with a region of large negative pitch angle. Here again, an explanation for this would be a vortex sheet shed from the tip of the blade. The wake region containing the vertical vortex sheet which is shed when going into the boundary layer is more obvious in Fig. 15 for this run than it was for run No. 2.

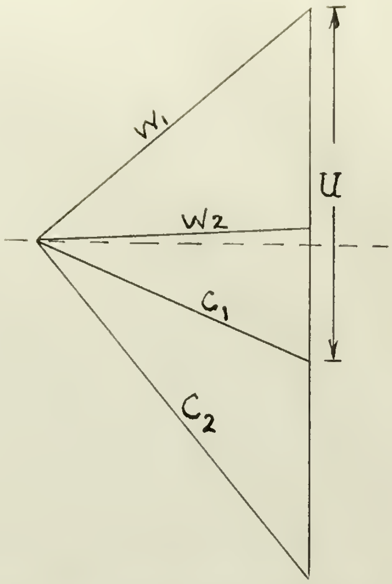
The main difference in the yaw angles between this run and run No. 2 is that the flow above the blade tips is strongly affected by the blades, and there are regions of overturning as in the case of no end clearance.

A study of Fig. 13 shows that the high energy fluid is being displaced upward along the pressure surface as in the case of the 5/16 inch end clearance run, but is not being displaced upward along the suction surface as in run 2. An explanation for this would be that the weaker shed horizontal vortex sheet in this case does not have sufficient strength to overcome the effects of "passage rotation" and the flow over the blade tips.

As in Run No. 2, the pitch angles greater than 15 degrees should be regarded only as indicating an order of magnitude.

Run No. 4 with 1/8 inch end clearance and a moving wall was made to simulate the relative motion between the housing and the rotor blade tips of a compressor. The results are shown in Figures 16, 17 and 18. The moving wall speed was the same as the inlet air velocity, which would be the relative entering velocity to a rotor row. These conditions and the blade angles give a velocity diagram as indicated below which is representative of the

diagram for a compressor rotor.



$W_1 = U$

Relative entering angle 40°

Relative exit angle 5°

The effect of the moving wall is immediately obvious from an examination of the yaw angles near the wall for this run and run No. 3. Here all the yaw angles near the wall are large positive angles indicating that the fluid near the wall is being dragged to the left with the moving wall.

The effect of the moving wall is also apparent when considering the region of high shear-high loss on the yaw and pressure maps for runs 3 and 4. In this run the area of high shear-high loss is both displaced in the direction of the moving wall and stretched horizontally.

Here again the vertical shed vortex sheet in the blade wake is apparent from an examination of Fig. 15. A difference in the pitch angles for this run and run No. 3 can be seen by comparing Figures 14 and 17. In general, the region near the wall showed a larger downward pitch angle in run 3 than in this run. No explanation is offered for this.

The high energy fluid is moved upward along both the pressure and suction faces in this run in a manner somewhat similar to run No. 2. An explanation of this would be that the horizontal vortex sheet shed from the blade tip is augmented by the moving wall, thus giving it greater effect in dragging high energy fluid up along the suction face.

A fact not immediately obvious from Fig. 16 is that the wall represents a line of 100% stagnation pressure as compared to a line of zero stagnation pressure for all other runs. With this fact in mind, a comparison of the losses in Fig. 13 for run No. 3 and Fig. 16 for this run becomes more understandable. By overlaying Fig. 13 and 16 one may obtain a definite indication that the losses with a moving wall are less than the losses without a moving wall. However, it must be remembered that energy is being fed into the stream in the case of the moving wall by the two motors driving the belt. In an actual machine, this extra energy would have to be supplied by the rotor itself.

It is estimated that if the energy added to the flow by the moving wall were subtracted, then the losses in runs 3 and 4 would be more closely comparable, with run No. 4 showing the greater loss.

The comparison of losses with and without a moving wall could be computed rather accurately by computing the momentum thickness of the belt boundary layer (in the Y direction) from a knowledge of the entering velocity profile in the X direction, the speed of the belt, the roughness or friction factor of the

belt, and the distance across the belt that the flow travels before reaching the probe. Obtaining the energy added to the flow in this manner, and computing the losses from Figs. 15 and 16 by graphical integration, a rather accurate comparison of the losses for the two runs could be made. This was not done due to lack of time.

CONCLUSIONS

In general, a moving wall effects the secondary flow by displacing the flow in the direction of the moving wall. The flow very close to the moving wall moves in the direction of the wall rather than turning with the main flow. In addition, the losses with a moving wall are probably greater, and definitely are confined to a region nearer the wall.

A comparison of all the pressure contours indicates that the losses with end clearance and with or without a moving wall are greater than with no end clearance. However, the region of losses is roughly the same as, or smaller with end clearance and with or without a moving wall than the region of losses with no end clearance.

Although a previous investigation with no end clearance (Ref. 4) indicates that losses do not increase appreciably farther downstream than 1/2 chord, it is believed that with end clearance with or without a moving wall, the losses would increase farther downstream than 1/2 chord because of high turbulence with resulting viscous dissipation.

Losses definitely increase with increased end clearance.

The flow in the boundary layer of a stator row (with no end clearance) overturns, producing a larger angle of attack on the following rotor row than designed. The flow in the boundary layer of a rotor (with a moving wall) underturns and makes a smaller angle of attack with the next stator row than the designed angle.

Experimental Equipment

This investigation was conducted with the low-speed wind tunnel at the Gas Turbine Laboratory. The wind tunnel has a velocity of the order of 120 feet per second. Details of construction and testing of the wind tunnel are found in Refs. 5, 6 and 7. The test section was modified prior to this investigation to facilitate the interchange of cascades and to make it readily adaptable to use with a moving wall.

The cascade was designed by Prof. Robert C. Dean, and consisted of NACA 6409 profiles on a circular arc mean camber line of 4.650 inches radius. The chord length was 2.800 inches; the spacing was 2.800 inches; the height was 16 inches, and the angle of incidence was zero.

A moving wall mechanism was constructed for use in this investigation of the effects on secondary flow of relative motion between the wall and the blade tips. A view of the moving wall assembly alone is shown in Fig. 1 and the assembly in place above the cascade is shown in Fig. 2.

An attempt was made, prior to this investigation, to use a belt made of shim stock for the moving wall. This material proved to be unsatisfactory. After considering several other belting materials, it was decided to use standard sanding belts. It was later learned that this method had been used successfully in other cascade work. (Ref. 2). The effect of surface roughness, comparable to surface finish of turbomachinery housings, could be investigated by varying the sanding belt grit size.

The moving wall was constructed in the following manner:

a section of 7-inch channel iron 5 feet long was used as a main support for the apparatus. Two wooden pulleys, 6 1/2 inches in diameter and 9 inches long were mounted underneath this channel, and a standard sanding belt 8 inches wide by 107 inches long was used on the pulleys. One pulley was made adjustable in order to vary the belt tension.

The lower half of the belt was used as the moving wall, and a backing plate for this section was constructed from a 10-inch channel iron, 28 inches long. The surface of the channel was ground smooth, and it was also suspended from the main support channel described above.

Originally one pulley was used as a drive for the moving wall, but later both pulleys were used as drives due to the fact that the motor was overloaded when only one was used. The motors used were rated at 115 volts, 1120 watts, 15,000 rpm, and were controlled by two variacs.

Until the wooden pulleys were dynamically balanced it was impossible to obtain a speed above about 63 feet per second on the belt due to severe vibration. After balancing, however, it was possible to obtain speeds up to 200 feet per second with no vibration and without using maximum power available.

During the investigation of the effect of the moving wall, it was necessary that the belt run in close contact with the backing plate in order to maintain a set clearance between moving wall and the ends of the blades. Originally it was supposed that this problem of keeping the belt in close contact with the backing

plate would be a serious one and methods were considered for applying a suction which would hold the moving belt in contact with the backing plate.

During the initial operation of the belt, however, it was found that it would not be necessary to apply suction since satisfactory contact with the backing plate was maintained in the speed range in which the moving wall was to be operated in this investigation. At low speeds (30 to 40 feet per second belt speed) the belt did not maintain proper contact with the backing plate. At speeds of 55 to 70 feet per second, however, the belt moving over the backing plate generated its own suction, and the belt was held in such close contact that the friction would decelerate the belt until it reached the low speed region where suction was lost. With the power setting remaining the same, this cycle of generating and then losing suction continued, the range of speed being from about 55 to about 70 feet per second during the cycle. By increasing the power it was possible to drive the belt through the "high suction" speeds, and at any speed above about 75 feet per second the suction generated by the belt was sufficient to maintain good contact with the backing plate but not so great that the friction would cause the belt speed to vary. At the higher speeds there was apparently a thin film of air dragged in between the backing plate and the belt, and this thin film of air acted as a lubricant. There seemed to be only a moderate amount of friction between the belt and the backing plate, because the temperature of the backing plate would rise a very small amount during long periods of operation of the belt.

The belt speed was determined by means of a generator tachometer mounted on one of the motors, and by a strobotach. Slippage of the belt on the pulleys varied both with speed and with belt tension, but the amount of slippage was found to be constant with a particular belt tension and speed. It was necessary to relieve the tension on the belt when it was not in use in order to avoid stretching the belt out of shape. When the rig was made ready for running it was not possible to obtain exactly the same tension each time, and therefore it was necessary each time the rig was used to obtain the correct belt speed by using the strobotach on a mark on the belt. Then with the belt running at proper speed, the voltage of the tachometer generator was noted, and it was found that the belt speed could be maintained constant by keeping a constant value of tachometer generator voltage. The adjustments in power to the motors to obtain constant speed throughout a run were very small.

The entire moving wall assembly was mounted on the main cascade support frame by means of two pads which supported the ends of the seven-inch channel as shown in Fig. 3. The method of varying the clearance between the blade tips and the moving wall, was to remove shims from between the frame comprising the cascade and the cross-piece of the main cascade support frame on which it rested. With shims removed the cascade was lowered, locating the tips of the blades below the level of the top of the wind tunnel test section. The moving wall assembly was placed in position by shimming and by adjustment of the backing plate

until the belt was on the same level as the top of the test section and the backing plate rested against the face of the test section.

INSTRUMENTATION

The instrumentation used during this investigation was basically the same as that used during a previous investigation by Van Le; using the low speed wind tunnel. Some modifications were made to improve the accuracy of readings, and to improve the speed and ease of obtaining readings. Instruments used and their arrangement are listed below.

A total pressure probe was mounted in the plenum chamber upstream of the converging section of the nozzle, and was used to maintain a constant value of stagnation pressure during a run. This probe was connected to one side of an inclined water manometer, the other side of which was connected to static pressure in the cell below. This was necessary because of the fluctuations of the static pressure in the test cell.

Originally a vertical total pressure rake was mounted 8¼ inches upstream of the cascade in the constant area duct. The nine probes of this rake were connected to one side of a bank of vertical water manometers and gave an indication of the velocity gradient in the stream approaching the cascade. This rake was later removed due to the fact that it disturbed the flow in the blade passages directly downstream.

A traversing mechanism was used to position a probe for making measurements either ahead of or behind the cascade. Both the horizontal and vertical travel of the probe were controlled by lead screws with 10 threads per inch and had handwheels calibrated into

100 divisions, so that within the mechanical error of the equipment, it was possible to position the probe to within 0.001 inch.

The probe yaw (horizontal) angle could be changed by rotating the vertical shaft which held the probe. The angle was controlled by a selsyn and could be read either at the control station or on the traversing mechanism to 0.1 degree. The probe could not be moved in pitch (vertical) angle, so that pitch angle was obtained by reading the difference in total pressure between the top and bottom holes of the five hole probe, and then obtaining the angle from a calibration curve.

A Meriam water manometer which could be read to 0.01 inch of water was used as a standard for calibrating other manometers and pressure pick-ups, and for checking the accuracy of readings throughout all runs.

A five hole wedge probe, manufactured at the Gas Turbine Laboratory, was used during all the runs. It consisted of five stainless steel tubes, 0.016 inch inside diameter, all soldered together and ground to a 60 degree conical shape at the tip. The diameter of all the tubes was 0.085 inch. The center hole was used for stagnation pressure, the side holes were for nulling to obtain yaw angle, and the top and bottom holes were for pitch angle. The response of this probe was very fast considering the diameter of the holes. A general view of the probe is shown in Fig. 4.

PROCEDURE

Since the constant area duct leading to the cascade had been lengthened slightly prior to this investigation, it was necessary to determine if the velocity profile at the outlet of the duct was still satisfactory. This was done by making a complete traverse in a plane 4½ inches upstream of the duct outlet (Plane A) with the cascade and rake removed. The results of this preliminary run showed a good profile for the area which would lie between blades 3 and 6, the area which was eventually used for all runs. The velocity profile and the contours of stagnation pressure are shown in Fig. 5. The flow direction was also found to be uniform and parallel to the axis of the duct.

Next it was necessary to determine if there was any flow separation on the blades of the cascade. Separation had been discovered on the blades used in a previous investigation with this wind tunnel, due primarily to the low turbulence in the air stream, and the difficulty had been overcome by installing trip wires or spoilers on the suction sides of the blades about 1/3 chord length behind the leading edge, as explained in Ref. 4. The method used to check for separation was to paint the blades with a solution of lampblack and kerosene and then observe how the air flow affected this solution when the tunnel was running at full speed. This method gave an excellent visual indication of the flow along the blades, and showed that separation and backflow was occuring on both the suction and pressure sides of the blades. It was found that trip wires, 0.006 inch in

diameter, located 33% chord from the leading edge on the suction side and 7.4% chord from the leading edge on the pressure side, would cause the boundary layer to stick and thus prevent separation.

After these preliminary steps, runs were made as described below.

Run No. 1, the first run for the purpose of obtaining data for this investigation, was with the cascade in place but with no end clearance and with no moving wall. In order to obtain the desired information with the minimum amount of data, it was decided to use only one complete blade passage and a small section of the two adjoining blade passages. Also, it was considered desireable that the portions of the three passages have approximately the same flow characteristics.

It was found that no three adjacent blade passages in the cascade were sufficiently similar in their flow pattern for the purposes of this investigation, except possibly those directly downstream of the profile rake. These passages had been eliminated because of the disturbance caused by the rake itself. After removal of the rake, three similar passages were found in the region originally eliminated because of the rake disturbance. The passage used for this and all subsequent runs was taken between blades 4 and 5, together with the edges of the two adjoining passages.

All the runs were made in a plane ½ chord length downstream of the trailing edge of the cascade blades (Plane B), since this is a representative figure of the distance separating one blade row from another in a turbomachine, and information gathered in this plane

could be used in designing the following row of blades. The runs were made at a Reynolds Number of 170,000.

The procedure when obtaining a reading at a point was to position the probe, null the pressures in the right and left holes of the probe to obtain yaw angle, and read the stagnation pressure and pitch angle microammeters. The stagnation pressure was then converted to percent of midspan value, and the pitch angle was obtained from a calibration curve.

Data were obtained by setting the probe at a given vertical (Z) coordinate, and then taking readings across the passage by taking increments in horizontal (Y) direction. The stagnation pressure and yaw angle were plotted as the data were taken, the reference or zero direction being taken as the direction of the flow at midspan between blades 4 and 5, and the reference or 100% stagnation pressure being taken at the same point. Similar traverses were made across the passage at increasing values of Z until the effects of the boundary layer could no longer be measured; i.e., until the flow was the same as that at midspan. The rough data plot for Run No. 1 is shown in Fig. 6.

The readings obtained and used in the rough data plot were reproducible to within about 0.1 degree for yaw and pitch and 0.2 percent for stagnation pressure in a region of high stagnation pressure, and to within about 0.3 degree and 0.5 percent in a region of low stagnation pressure where the probe was less sensitive. However, except in a region of uniform velocity, the yaw and pitch angles

as read were not correct.

Since there was a finite distance separating the right and left holes of the probe, it was possible, with the probe in a region of steep velocity gradient, for the right hole to be in a region of high velocity while the left hole was in a region of low velocity. Under such conditions, the right hole would indicate a higher pressure than the left even though the probe was pointing directly into the stream. Therefore, when nulling to obtain yaw angle, the probe would be turned more to the right so that the pressures in the right and left holes would be balanced, and an incorrect value of yaw would be obtained.

The same reasoning applied to the top and bottom holes for obtaining pitch angle. In addition, the pitch reading on the microammeter was dependent not only on the actual pitch angle of the flow but also on the percent of reference stagnation pressure at the particular point. This was due to the fact that with the flow going in a given direction, the reading of the pitch microammeter and thus the pitch angle would show an increase with increasing stagnation pressure.

The yaw angles were corrected for velocity gradients by using the rough data plots to determine the actual difference in stagnation pressure between two points separated by a distance equal to the distance between the right and left holes of the probe (0.056 inch). This difference in stagnation pressure was then used to enter a curve and obtain the correction to the yaw angle. The corrected yaw

angles were then plotted on the same rough data plot, although they are not shown in Fig. 6.

It was found that the velocity gradients in a vertical direction were not severe enough to cause any appreciable correction to the pitch angles. Therefore the corrected pitch angle was obtained by noting the pitch microammeter reading, and the stagnation pressure at the point, and entering a previously prepared curve to obtain the pitch angle.

The rough data plot, with yaw and pitch angles corrected, was then used to prepare contour maps of the area showing percent of stagnation pressure, yaw angle, and pitch angle. These contour maps for Run No. 1 are shown in Figures 7,8, and 9 respectively.

Run No. 2 was made with a stationary wall, but with an end clearance of 5/16 inch, or 11.2% chord. Data was obtained and plotted in the same manner as that described for Run No. 1, and the results are shown in Figures 10, 11, and 12.

Run No. 3 was similar to the second run except that the end clearance was 1/8 inch or 4.5% chord. Data was obtained and plotted as before and the results are shown in Figures 13, 14, and 15.

Run No. 4 was similar to the third run, except that the moving wall was used during this run, with the velocity of the moving wall being equal to 120 feet per second. The sanding belt was 600x grit. The data was obtained and plotted as before, and the results are

shown in Figures 16, 17, and 18. It was necessary to correct pitch angles in this run due to the high velocity gradients in the vertical direction.

RECOMMENDATIONS

From a study of the results obtained in this investigation it was evident that much more data is required to fully evaluate the effects of relative motion between blades and wall on the secondary flow. It is recommended that traverses be made holding all variables constant except one, and attempt to obtain an idea of the relative importance of end clearance, belt speed, belt roughness, and entering boundary layer. It might be possible to find the one combination of the variables which would produce the smallest losses, or the one combination which prepared the flow for the next row in the best manner.

In order to have a better understanding of the development of the flow phenomena, it is recommended that additional traverses be made in planes nearer the trailing edges of the blades, and also within the blade passages themselves. The traverse of the plane one-half chord length downstream of the cascade, although indicative of the flow that might be entering the next set of blading in a turbomachine, does not give enough information to visualize the upstream flow development.

It is further recommended that the traversing mechanism be modified to permit nulling the probe to obtain pitch readings. This modification would permit nulling for both pitch and yaw angles. Angles could then be obtained directly and would only require correction for regions of high velocity gradient.

An investigation on the probe types and of procedures for obtaining reliable data in high velocity gradients is recommended. This study would be made with the objective of developing a procedure that would permit rapid translation of readings obtained to corrected values.

A method of readily presenting the data in three dimensions would be of great value in the interpretation of results. Two dimensional plots have limited value in the visualization of the flow pattern. One method of presentation which could be used to advantage in presenting such data would be five dimensional needle plots, one of which has already been prepared at the Gas Turbine Laboratory. In this method, a piece of board is used to represent the plane of measurement (in this case plane B). Over the entire area of the board at equal intervals are placed needles pointing in the direction of the flow at the point, and with a length corresponding to the stagnation pressure. Thus one plot indicates the dimensions of Y and Z location of the point in plane B, yaw angle, pitch angle, and percent of stagnation pressure.

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APPENDIX A

SMOKE GENERATOR

An investigation was made of suitable means for producing a smoke stream for visualization of the flow in the cascade. A smoke generator, developed by the Ultrasonic Corporation of Cambridge, Massachusetts, in conducting basic research on control of particle size, was obtained. As originally constructed, the smoke generator consisted of an electrically heated tank for vaporizing oil, a thermometer, a pressure switch for regulating the vapor pressure in the tank, and a short outlet line for the vapors. It was intended to use this smoke generator as originally constructed, except that the short outlet line would be replaced by a rather long (5 feet) line leading to a smoke probe. A diagramatic sketch of the equipment is shown in Fig. 1-A.

The tank was constructed of a section of 4 inch pipe, with a fitting at the bottom to receive the 1000 watt Cromalox immersion type heater, and fittings at the top for a thermometer, a pressure line, and an outlet line for the oil vapor. The total capacity of the tank was approximately three quarts. During operation the oil level was maintained at about one inch above the top of the heating element, leaving approximately four inches of the tank for vapor space.

The vapor pressure in the tank was controlled by a pressure switch which controlled the current to the heater. The pressure switch consisted of a mercury manometer, one side of which led to

the tank and the other side of which was open to the atmosphere. In the column which was open to the atmosphere, there was mounted a small float made of plastic, which was connected by a rod to a mercury switch. An increase in pressure in the tank would cause the mercury level in the manometer to rise, raise the float, actuate the switch, and cut off the current to the heater. A variac was also in the line for better control.

The pressure maintained in the tank during operation could be varied from zero to 26 inches of mercury ; 16 inches of mercury was the pressure used during most of the investigation. The oil used was Socony Gargoyle "Velocite", Grade E. This oil had been used by Ultrasonic Corporation with satisfactory results.

It was found that the smoke generator, modified as described above, operated as a distilling apparatus. The oil vapor condensed, and the oil particles collected on the walls of the tubing and came out of the smoke probe as liquid oil. The only way of obtaining good smoke was to maintain the line leading to the smoke probe and the probe itself at a sufficiently high temperature to keep the oil in the vapor state until it emerged from the probe into the air. Even when this was done, some liquid oil was still observed leaving the probe.

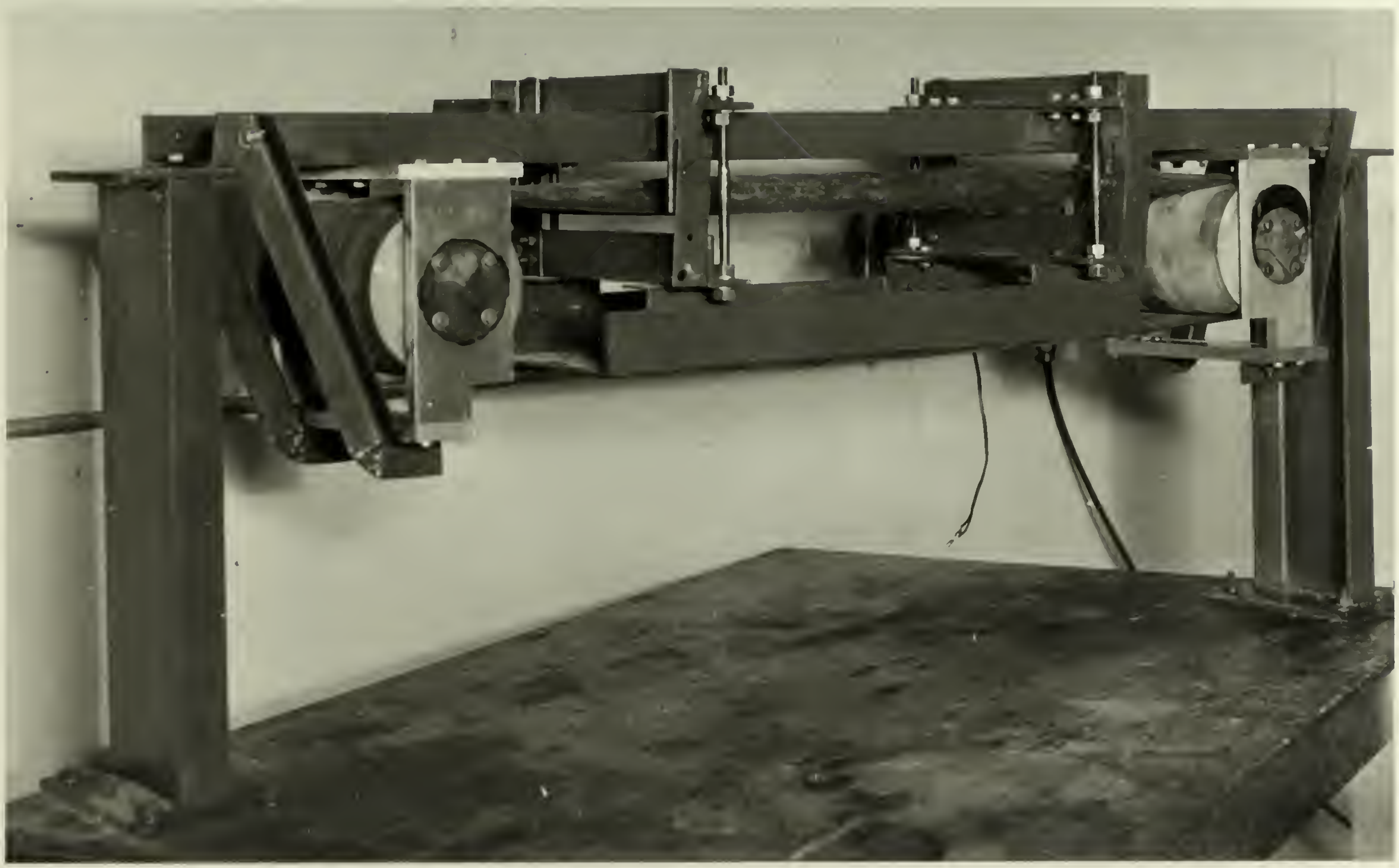
The failure of the basic equipment to function properly in this application, whereas it had worked properly for Ultrasonic, was attributed to the following difference in the operating conditions: In the work done by Ultrasonic, the vapor was taken from

the tank and injected directly into an air stream, rather than passing through a length of tubing and a flow stricture such as produced by a smoke probe of small diameter.

Following this line of reasoning, it was felt that if cool air could be injected into the vapor line near the tank, the smoke particles would remain in suspension until they had passed through the line and out of the probe. This method was attempted with unsatisfactory results.

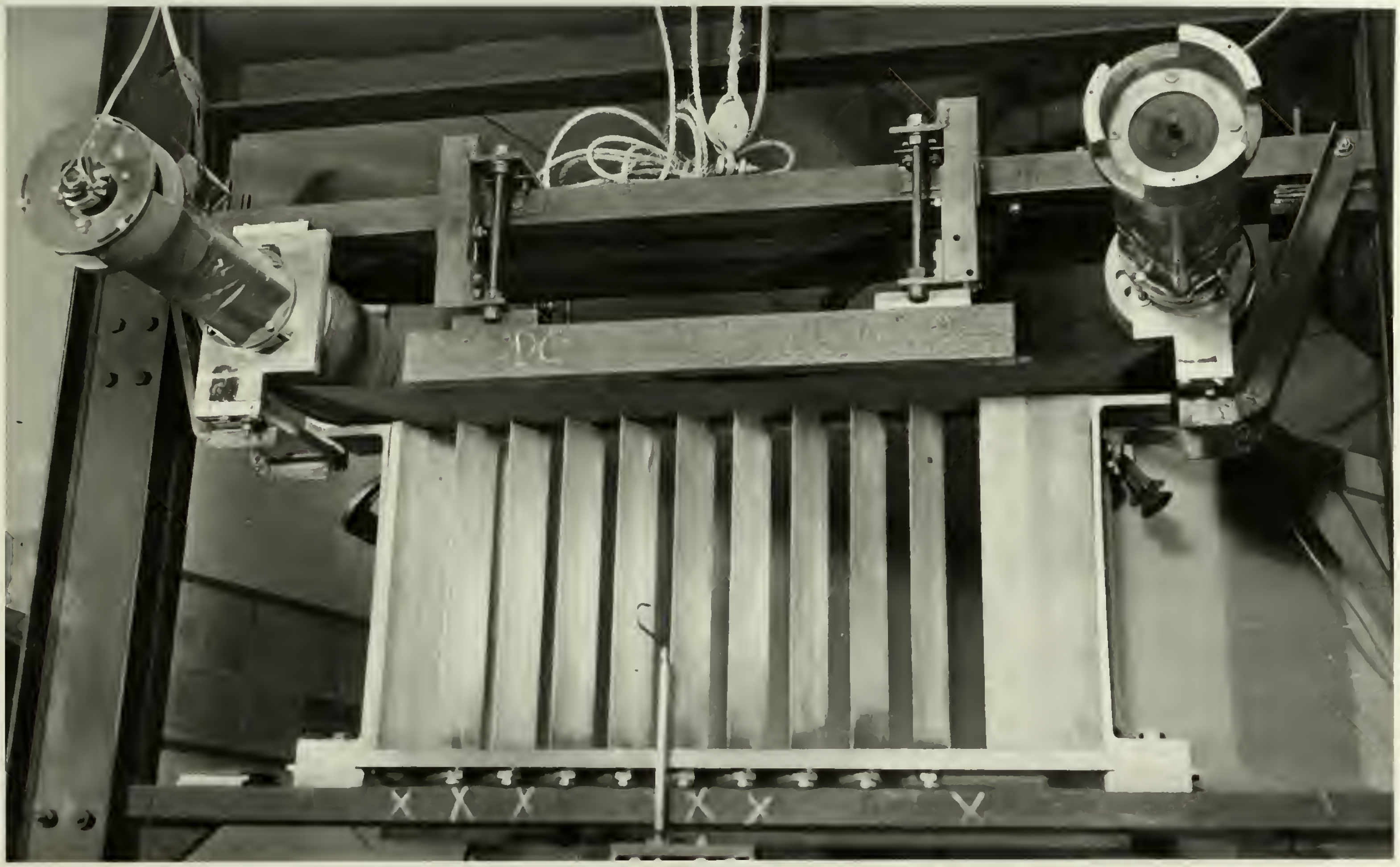
Another method considered was that of a settling tank near the vapor tank to fix smoke particle size before entering the line to the probe. This method was not tried.

A smoke generator, similar in principle to that described in Ref. 1 was used to investigate materials that would produce satisfactory smoke. Cork and cigars were used with good results. Oil soaked cigars proved most satisfactory. It was intended to use this type of smoke generator for visualization of the flow in the cascade.



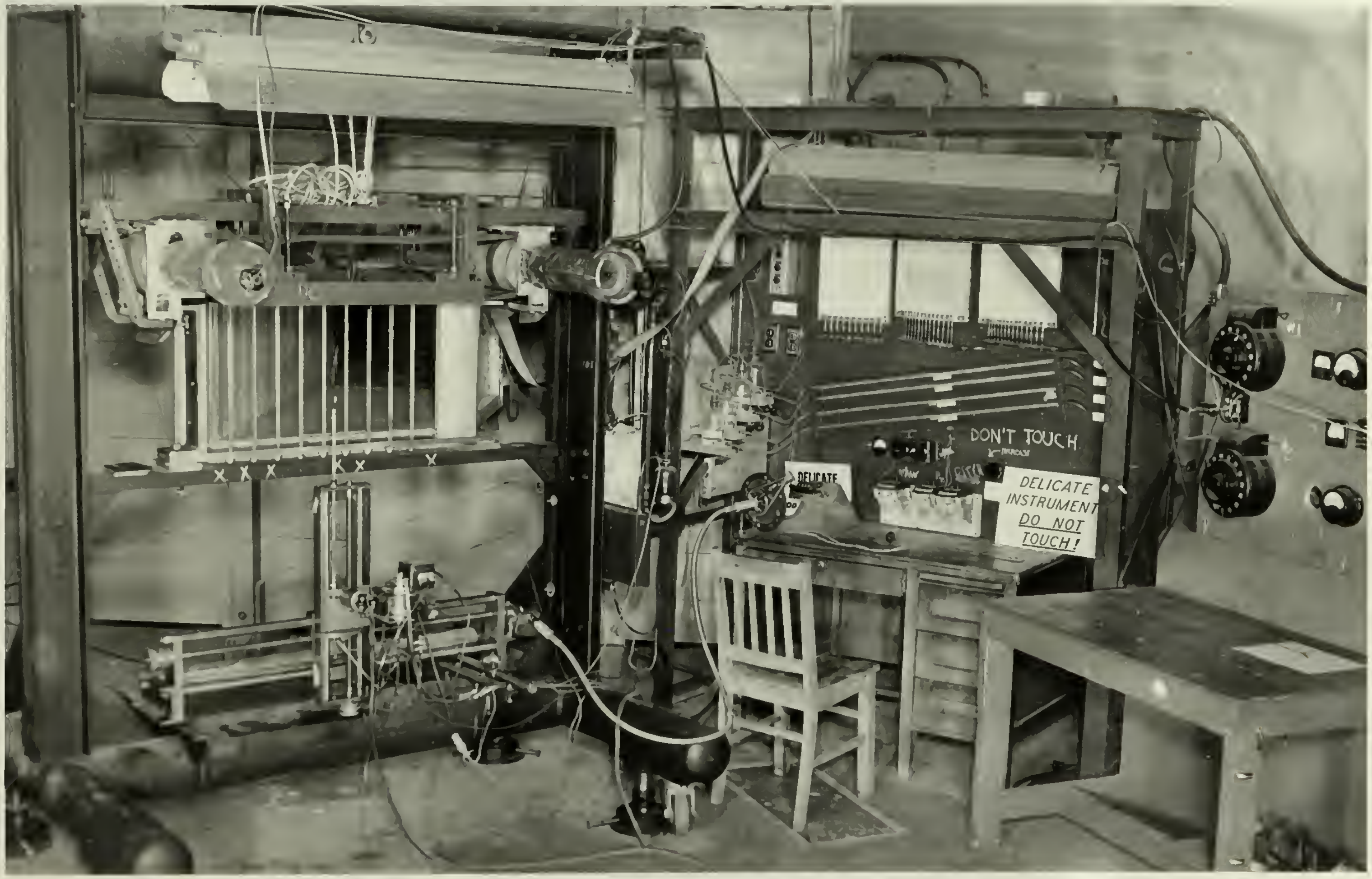
MOVING WALL ASSEMBLY

Fig. 1



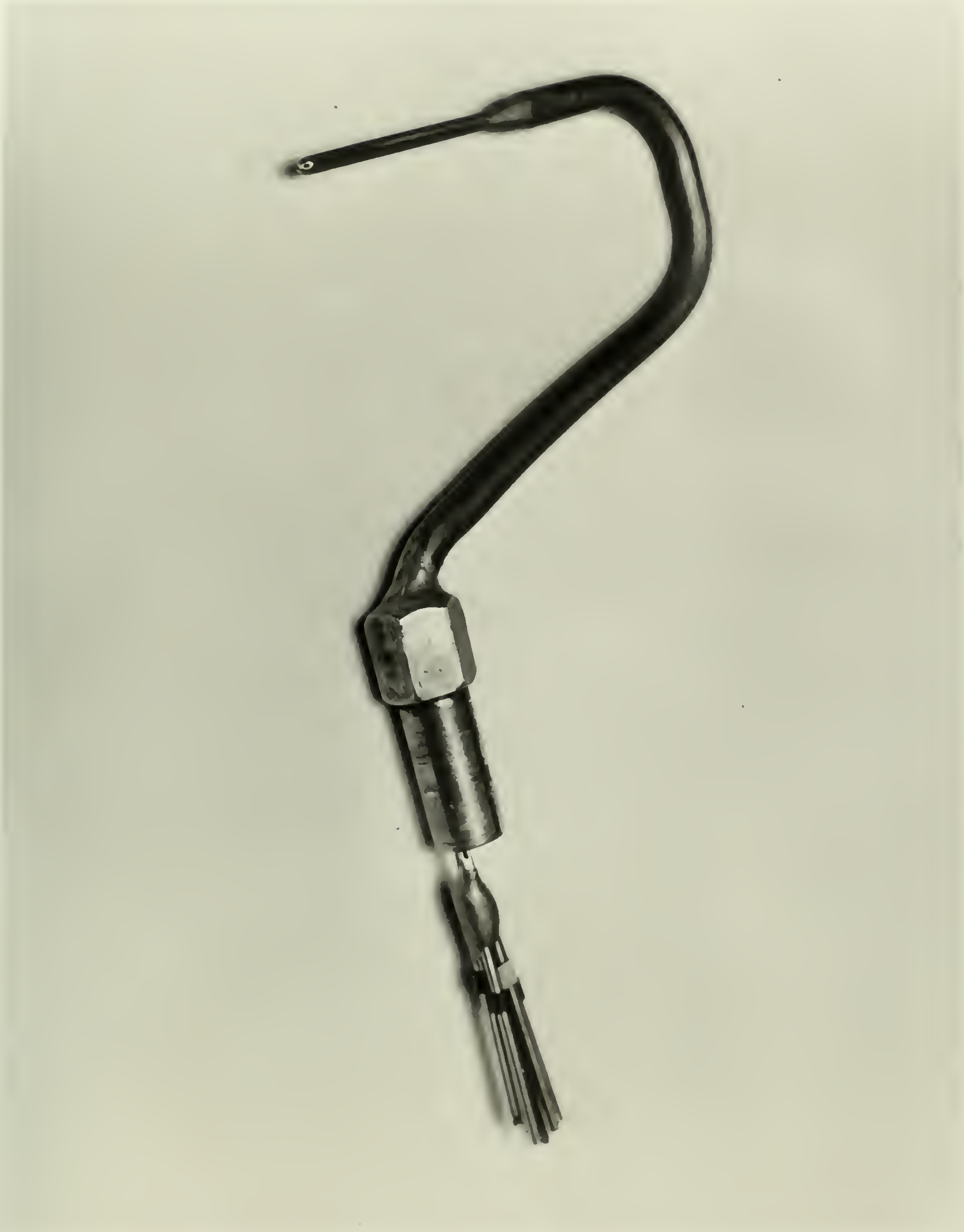
MOVING WALL ASSEMBLY MOUNTED ABOVE CASCADE

Fig. 2



GENERAL VIEW OF TEST SECTION AND CONTROL STATION

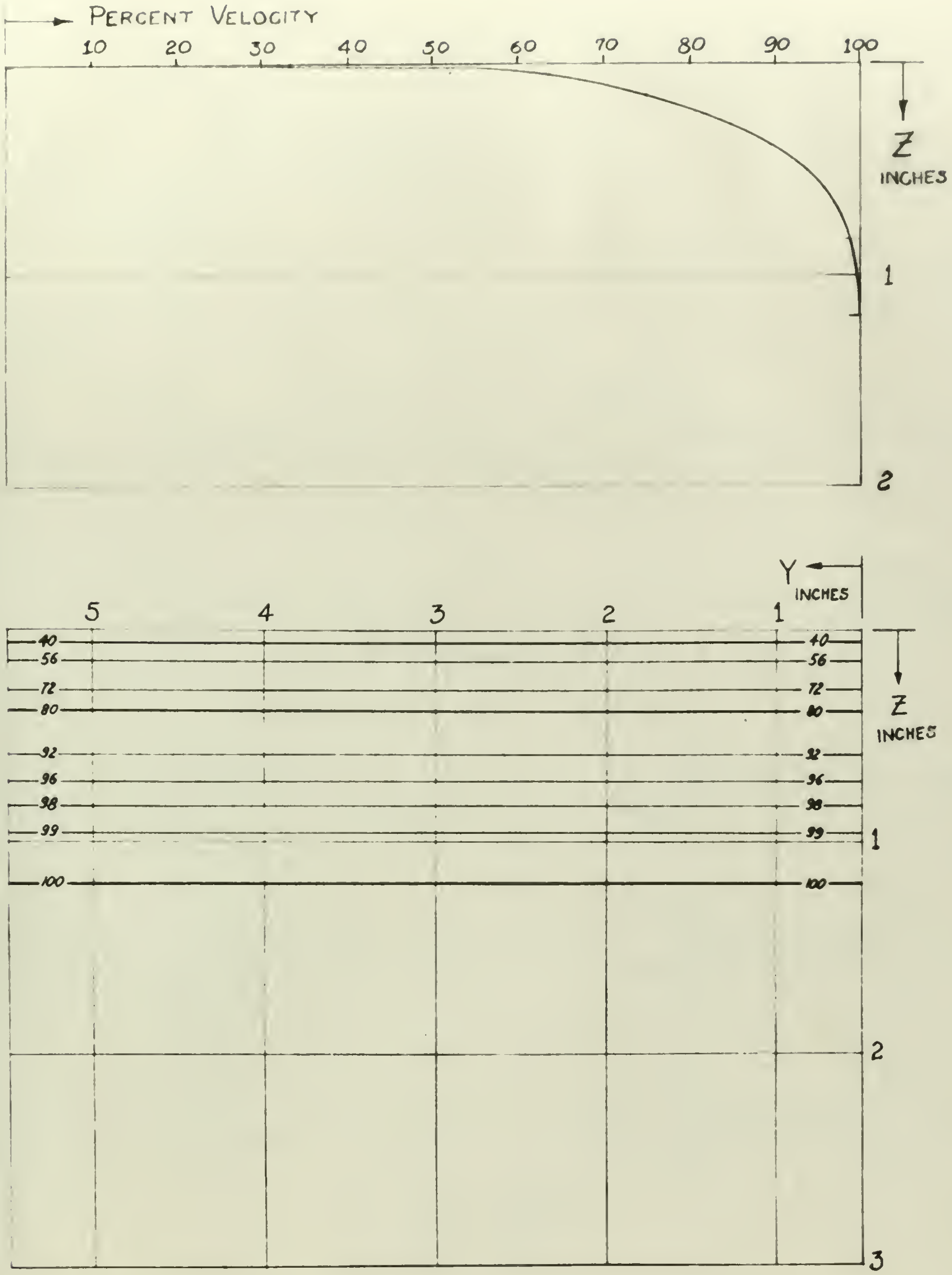
Fig. 3



FIVE HOLE PROBE

($1\frac{1}{2}$ Times Actual Size)

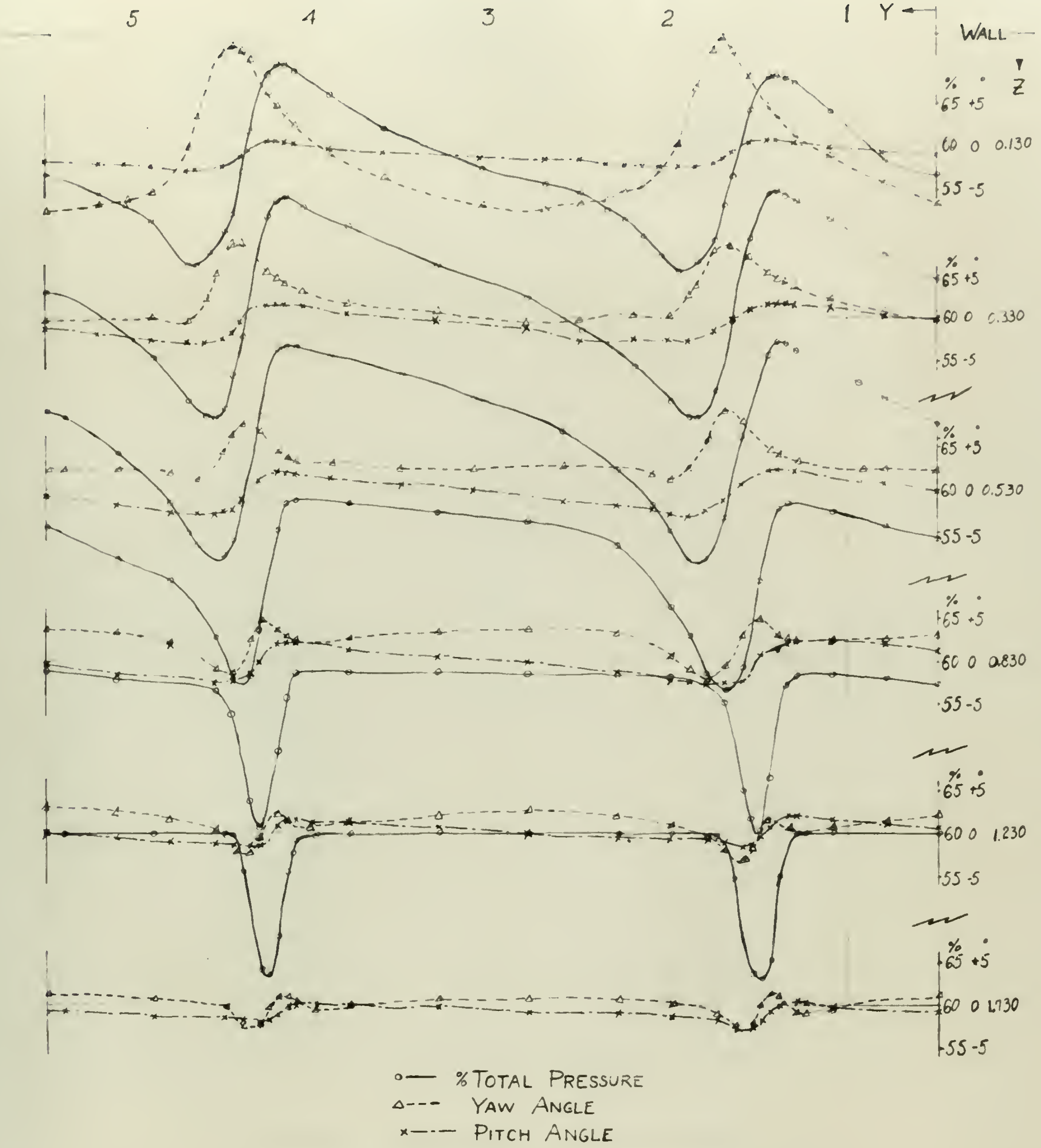
Fig. 4



VELOCITY PROFILE AND BERNOULLI SURFACES

IN PLANE A (Cascade Removed)

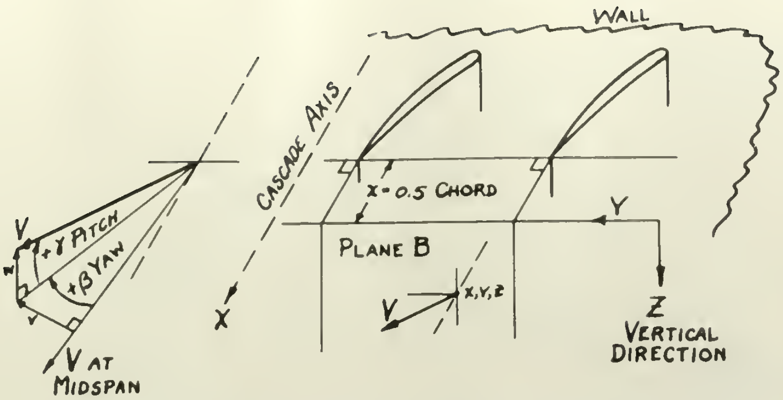
Fig. 5



ROUGH DATA PLOT

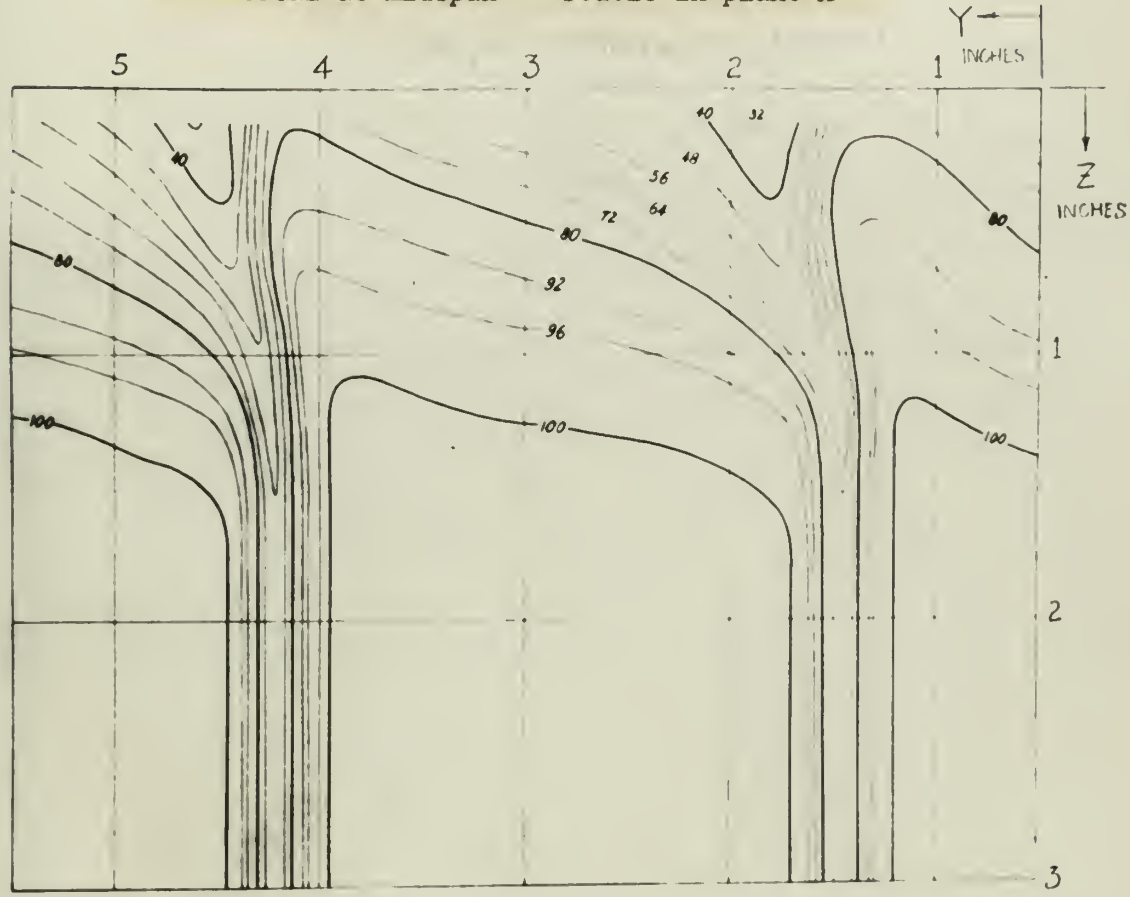
RUN NO. 1 (NO END CLEARANCE)

FIG. 6



Numbers on Contours Indicate

$$\frac{P_{total} - P_{static\ in\ plane\ A}}{P_{total\ at\ midspan} - P_{static\ in\ plane\ A}}\ \%$$

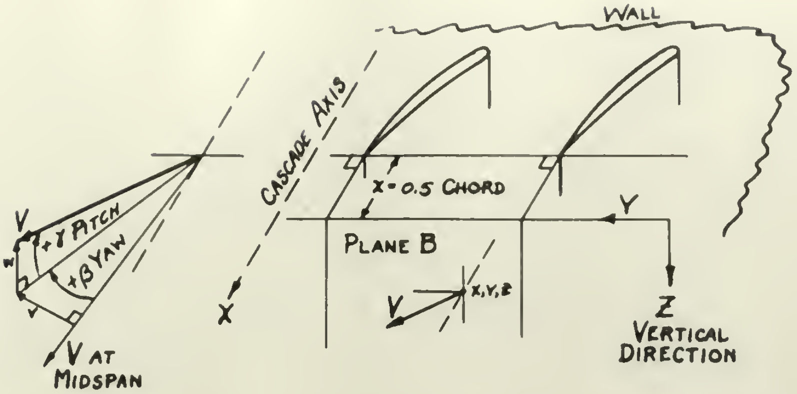


THE FLOW DOWNSTREAM OF A BLADE CHANNEL
OF A CASCADE

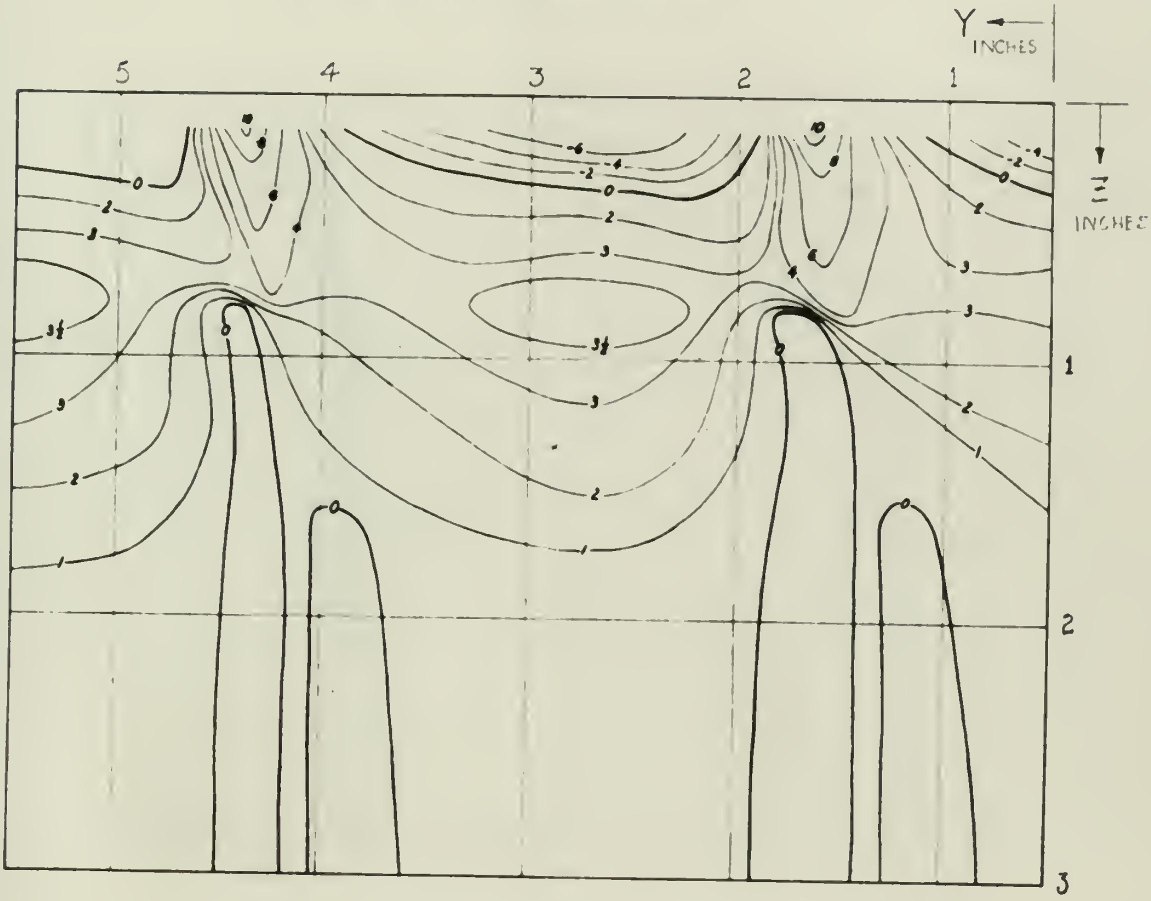
Distortion of Bernoulli Surfaces

Run No. 1 (No End Clearance)

Fig. 7



Numbers on Contours Indicate Yaw Angles as Measured From the Reference Direction at Midspan and Midway Between Blades

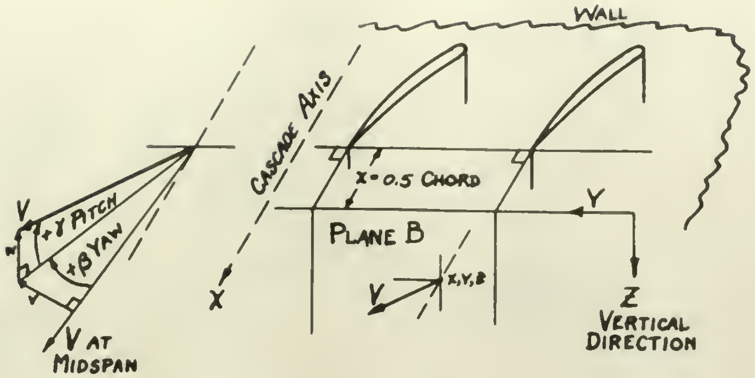


THE FLOW DOWNSTREAM OF A BLADE CHANNEL OF A CASCADE

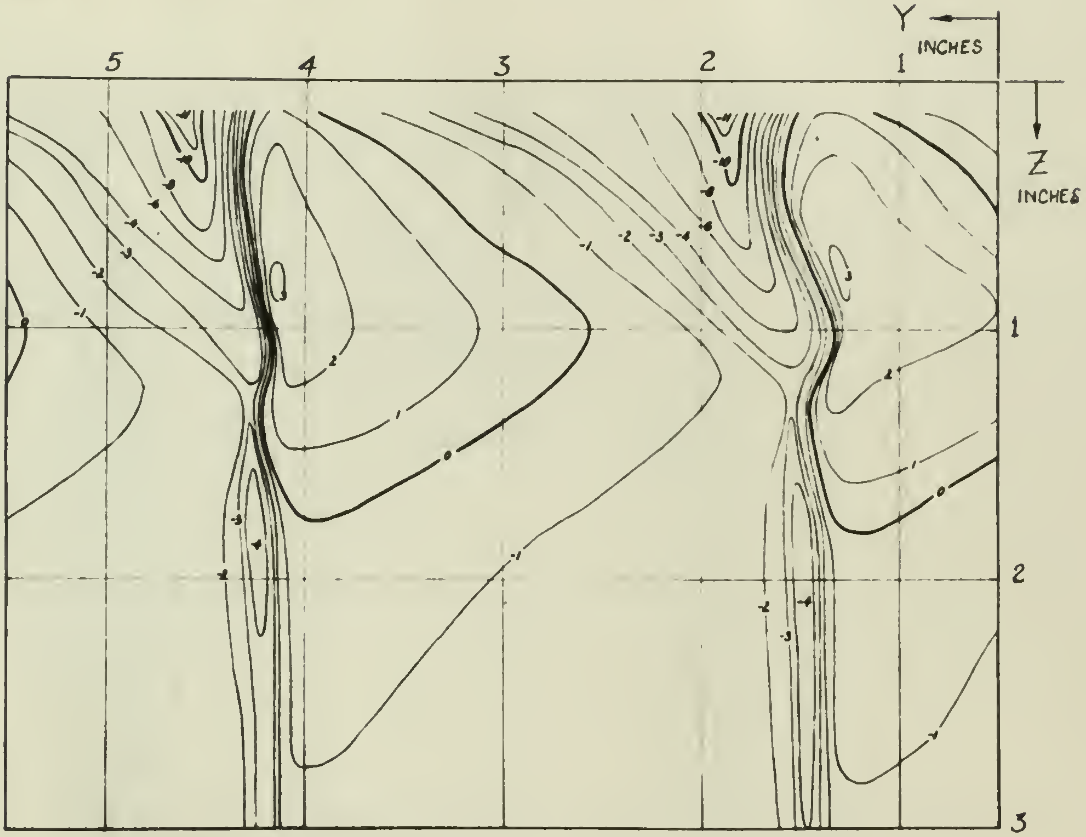
Contours of Yaw Angle

Run No. 1 (No End Clearance)

Fig. 8



Numbers on Contours Indicate Pitch Angles as Measured From the Reference Direction at Midspan and Midway Between Blades



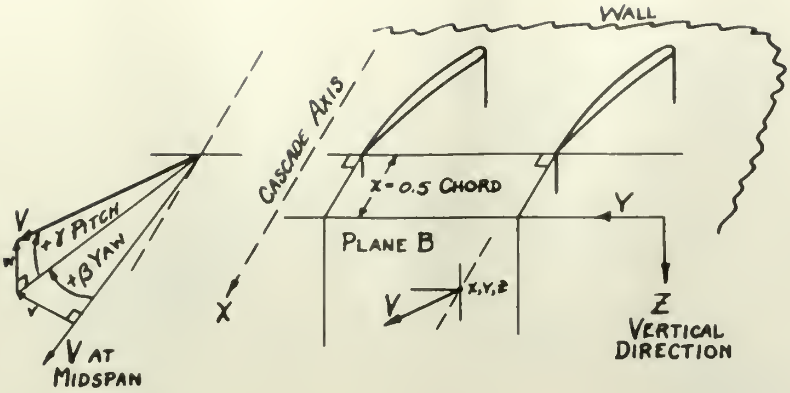
THE FLOW DOWNSTREAM OF A BLADE CHANNEL

OF A CASCADE

Contours of Pitch Angle

Run No. 1 (No End Clearance)

Fig. 9



Numbers on Contours Indicate

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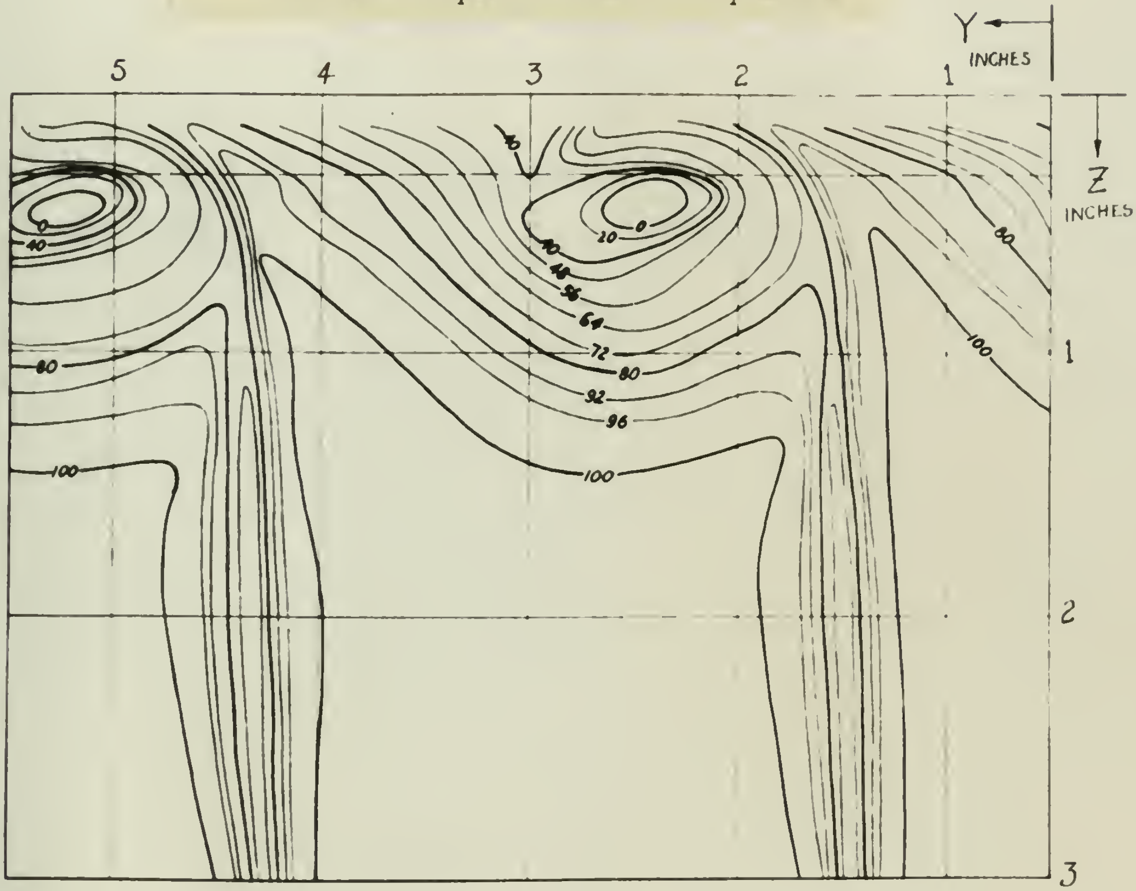
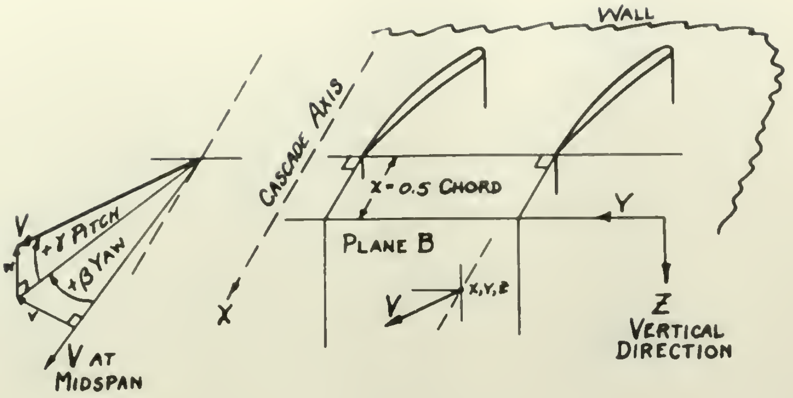


THE FLOW DOWNSTREAM OF A BLADE CHANNEL
OF A CASCADE

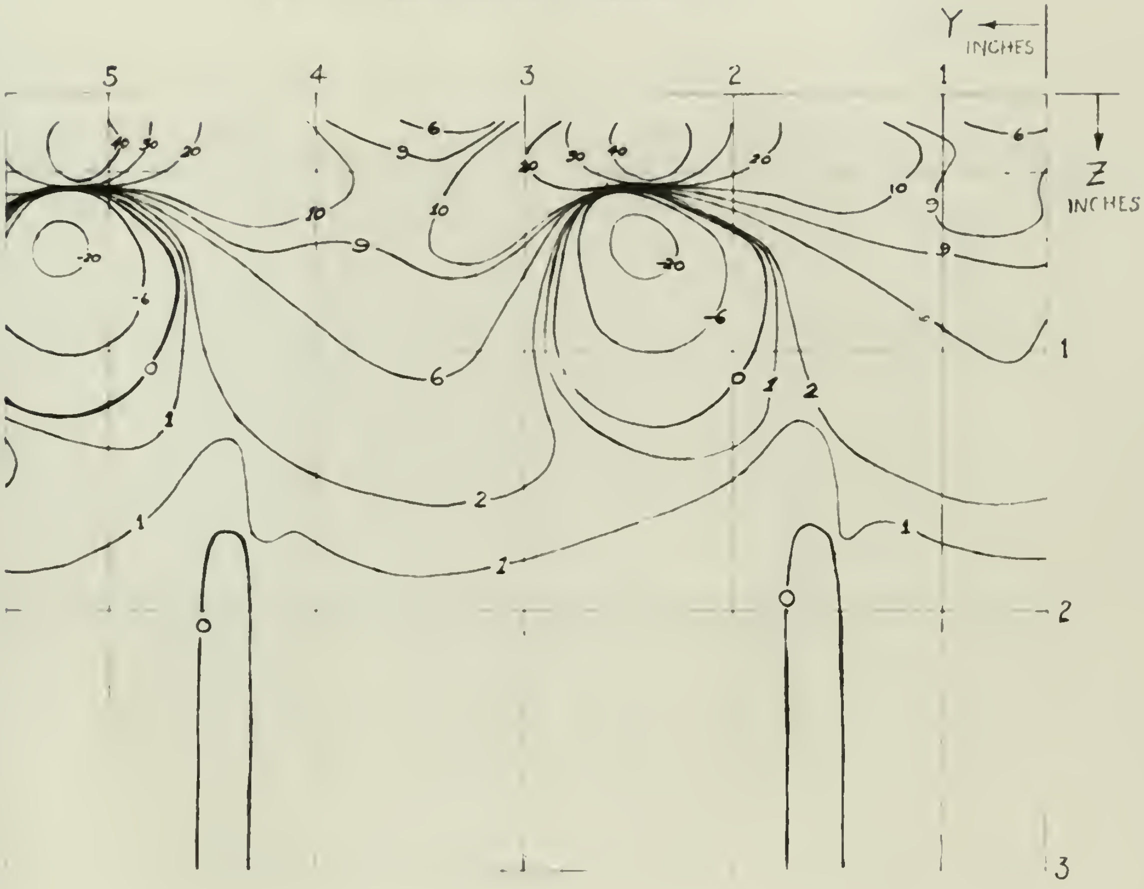
Distortion of Bernoulli Surfaces

Run No. 2 (5/16 inch End Clearance)

Fig. 10



Numbers on Contours Indicate Yaw
Angles as Measured From the
Reference Direction at Midspan
and Midway Between Blades

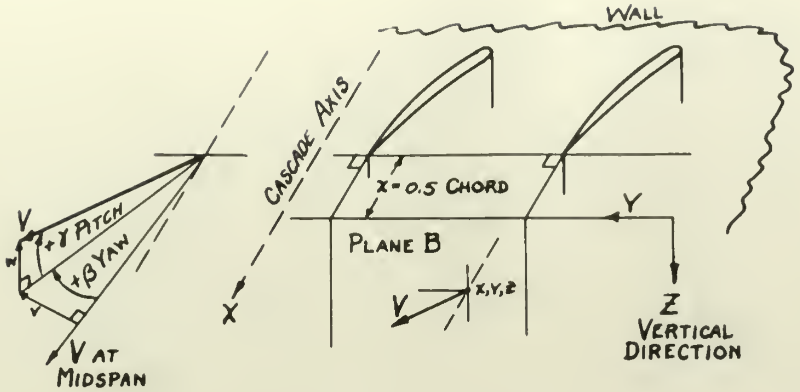


THE FLOW DOWNSTREAM OF A BLADE CHANNEL
OF A CASCADE

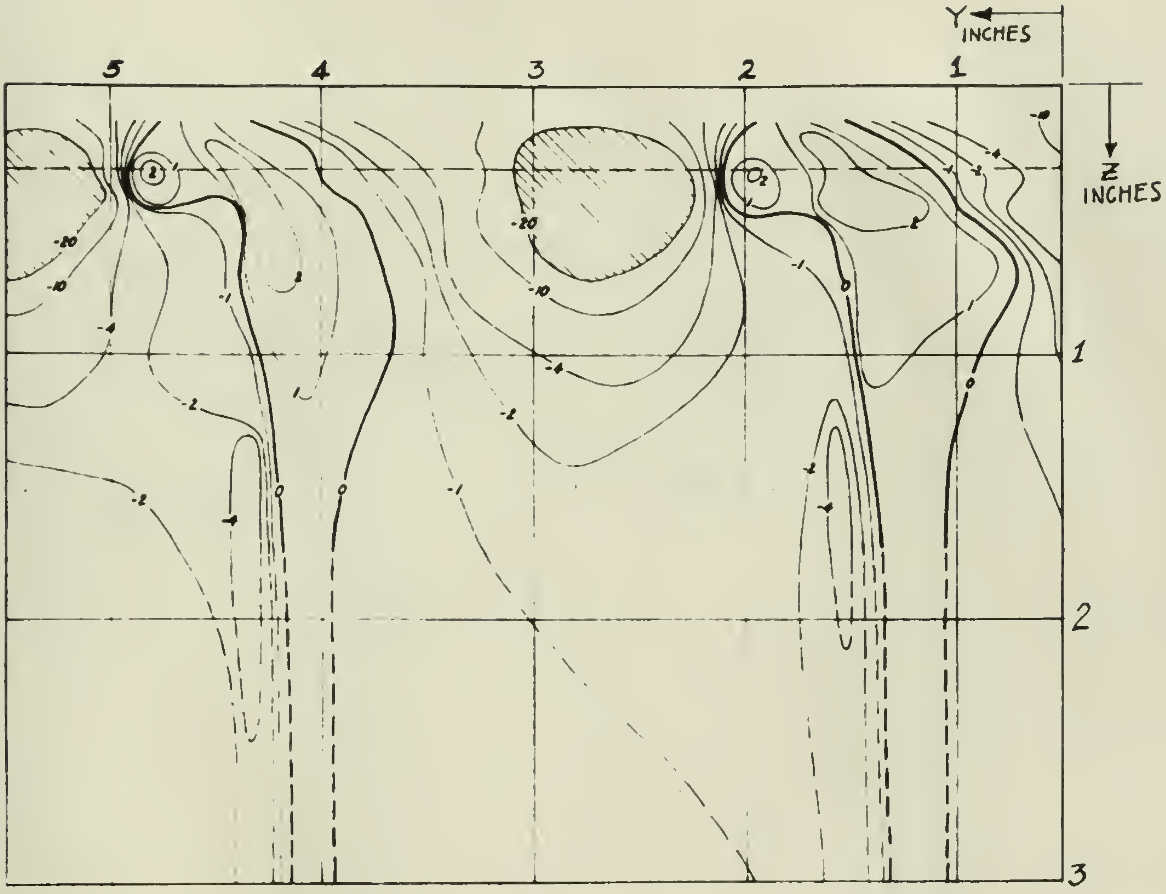
Contours of Yaw Angle

Run No. 2 (5/16 inch End Clearance)

Fig. 11



Numbers on Contours Indicate Pitch Angles as Measured From the Reference Direction at Midspan and Midway Between Blades

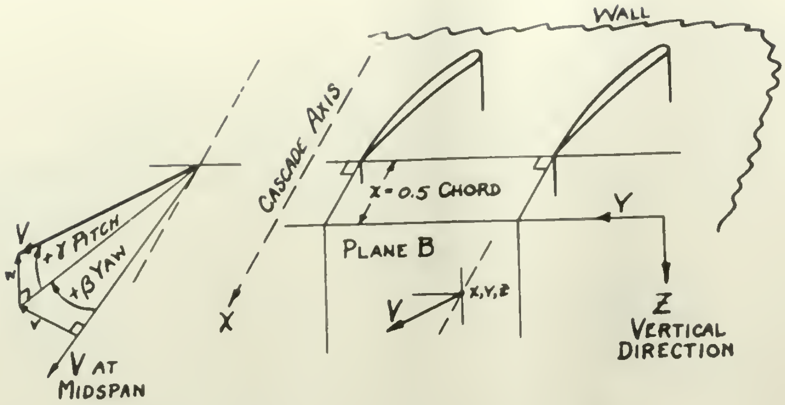


THE FLOW DOWNSTREAM OF A BLADE CHANNEL OF A CASCADE

Contours of Pitch Angle

Run No. 2 (5/16 inch End Clearance)

Fig. 12



Numbers on Contours Indicate

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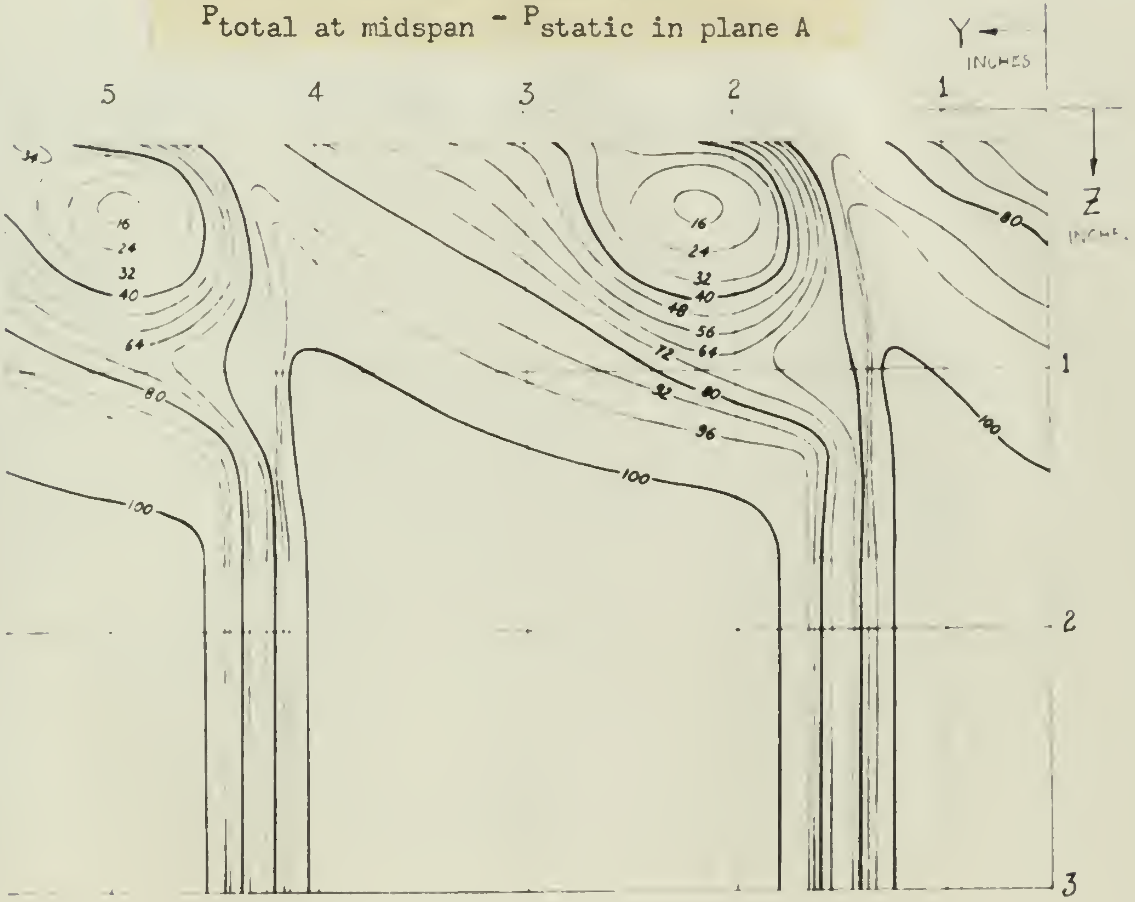


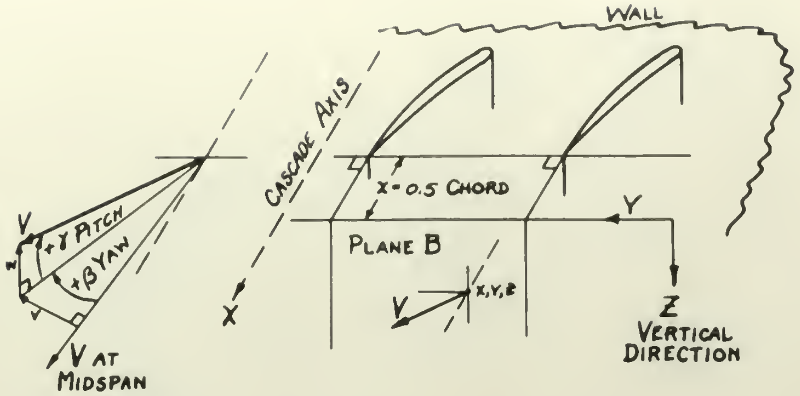
THE FLOW DOWNSTREAM OF A BLADE CHANNEL

OF A CASCADE

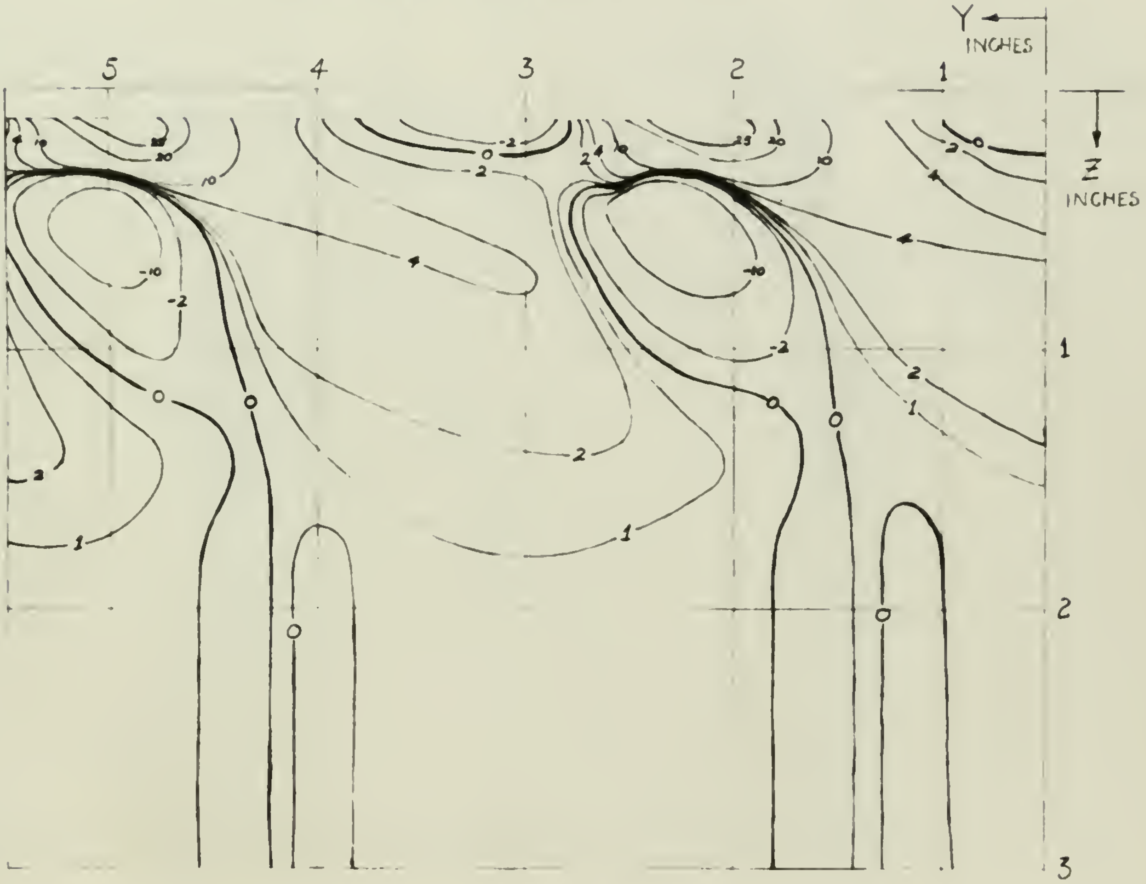
Distortion of Bernoulli Surfaces

Run No. 3 (1/8 inch End Clearance)

Fig. 13



Numbers on Contours Indicate Yaw Angles as Measured From the Reference Direction at Midspan and Midway Between Blades

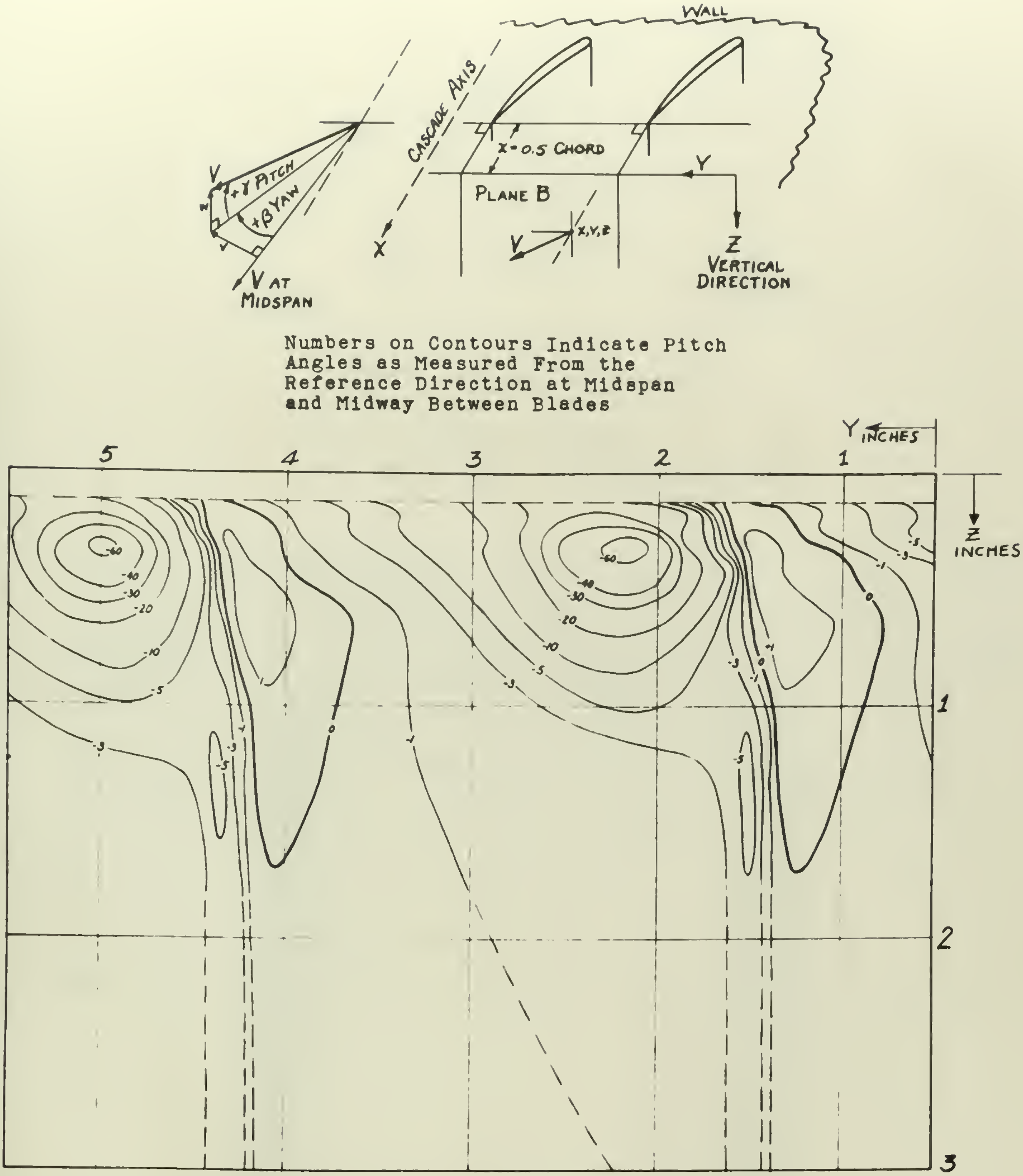


THE FLOW DOWNSTREAM OF A BLADE CHANNEL OF A CASCADE

Contours of Yaw Angle

Run No. 3 (1/8 inch End Clearance)

Fig. 14



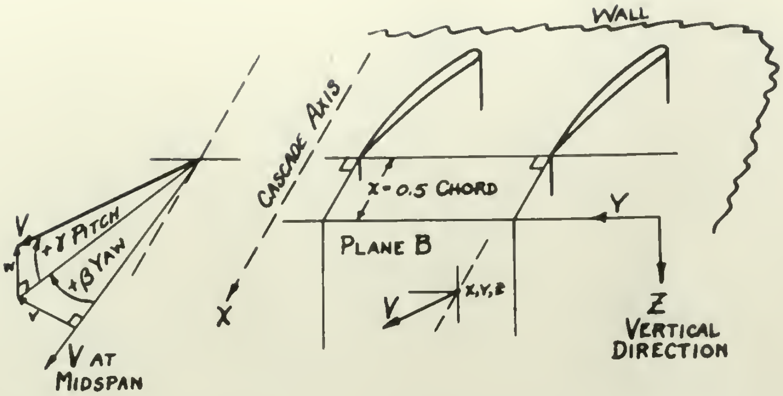
Numbers on Contours Indicate Pitch Angles as Measured From the Reference Direction at Midspan and Midway Between Blades

THE FLOW DOWNSTREAM OF A BLADE CHANNEL
OF A CASCADE

Contours of Pitch Angle

Run No. 3 (1/8 inch End Clearance)

Fig. 15



Numbers on Contours Indicate

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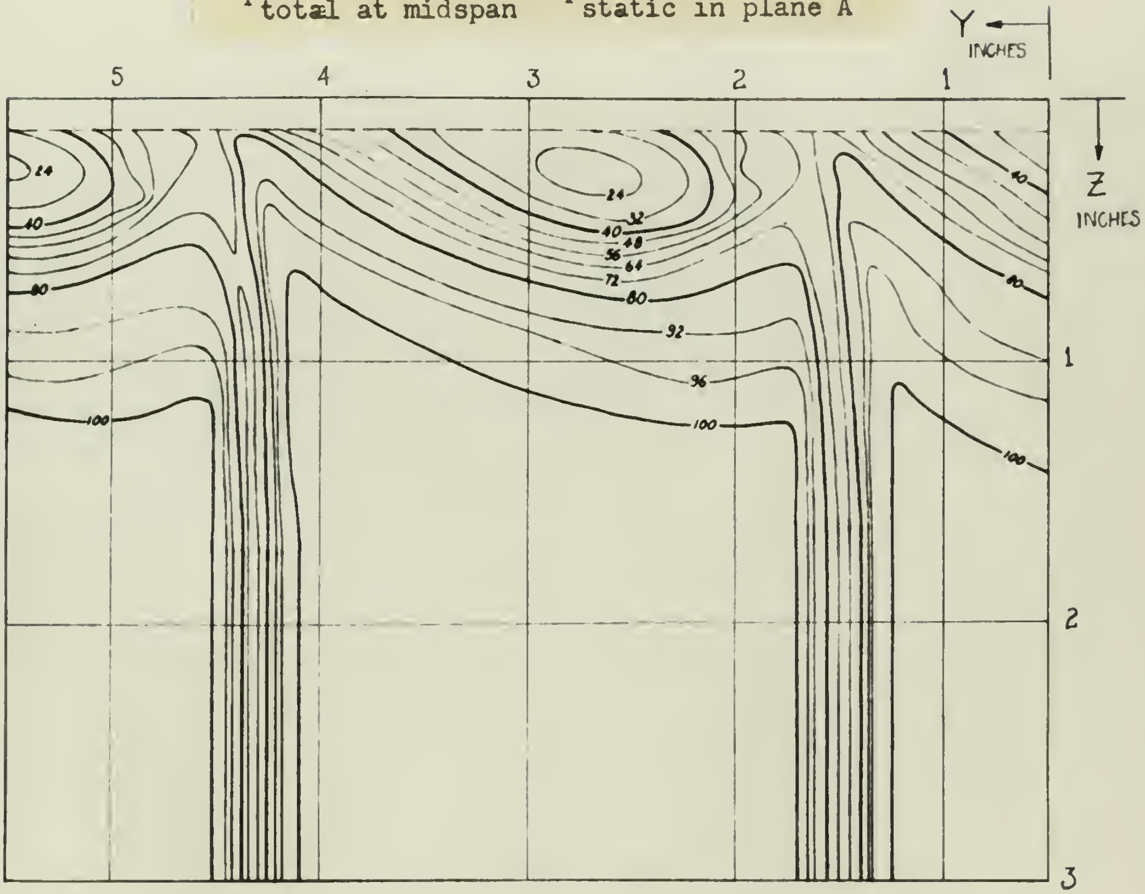
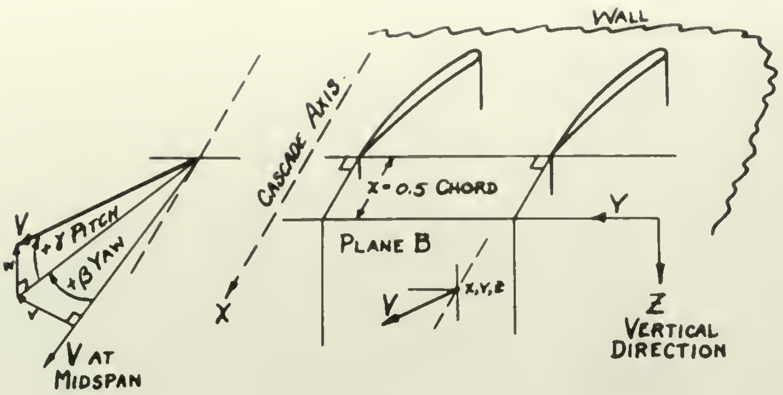


THE FLOW DOWNSTREAM OF A BLADE CHANNEL
OF A CASCADE

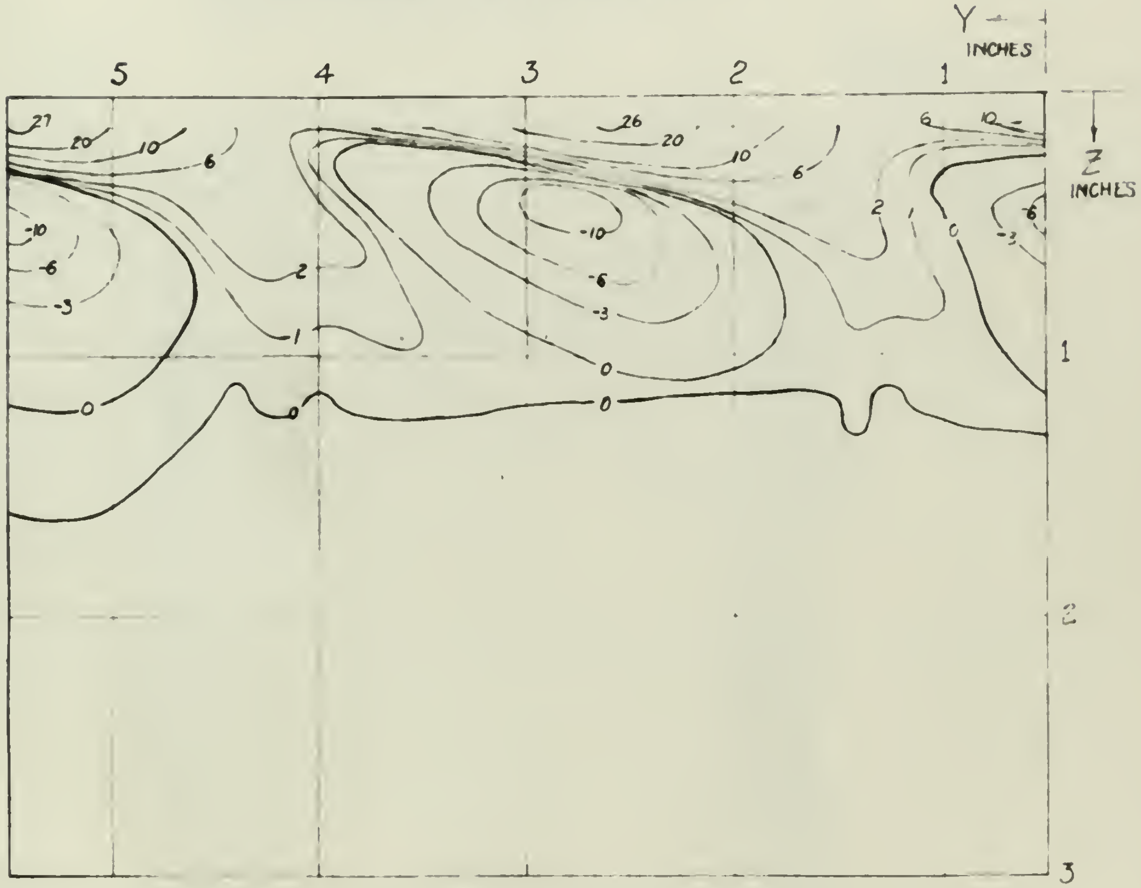
Distortion of Bernoulli Surfaces

Run No. 4 (1/8 inch End Clearance
With Moving Wall)

Fig. 16



Numbers on Contours Indicate Yaw
Angles as Measured from the
Reference Direction at Midspan
and Midway Between Blades



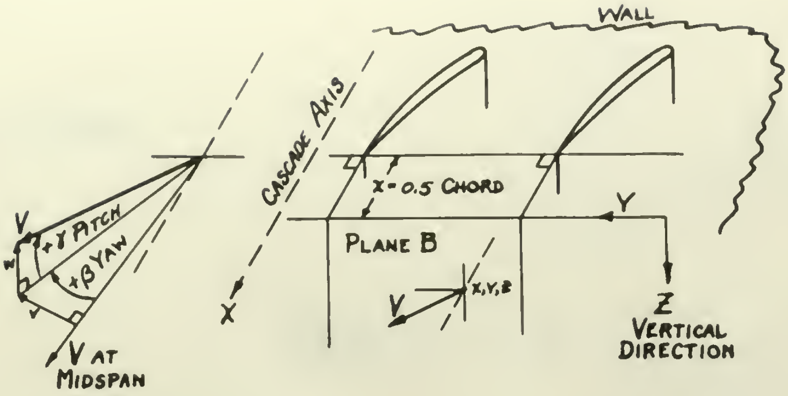
THE FLOW DOWNSTREAM OF A BLADE CHANNEL

OF A CASCADE

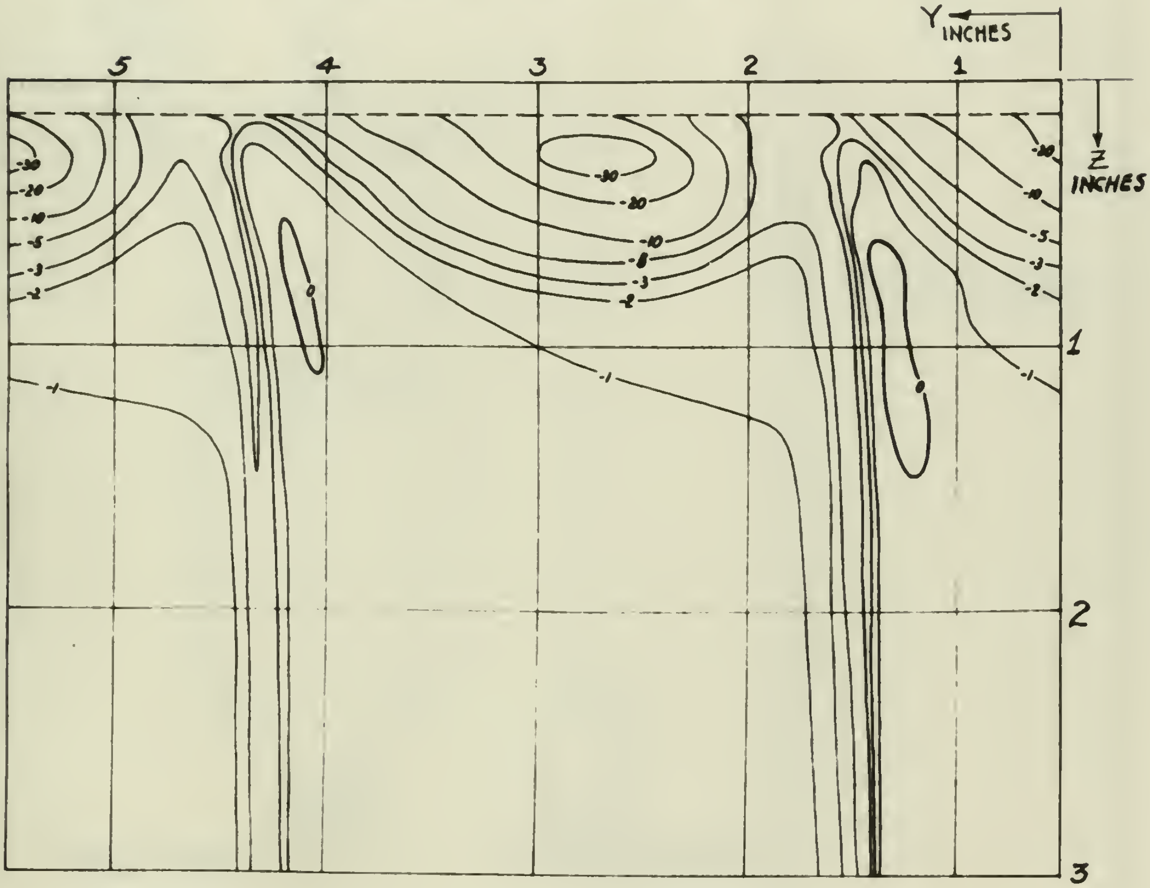
Contours of Yaw Angle

Run No. 4 (1/8 inch End Clearance
With Moving Wall)

Fig. 17



Numbers on Contours Indicate Pitch
Angles as Measured From the
Reference Direction at Midspan
and Midway Between Blades



THE FLOW DOWNSTREAM OF A BLADE CHANNEL
OF A CASCADE

Contours of Pitch Angle

Run No. 4 (1/8 inch End Clearance
With Moving Wall)

Fig. 18

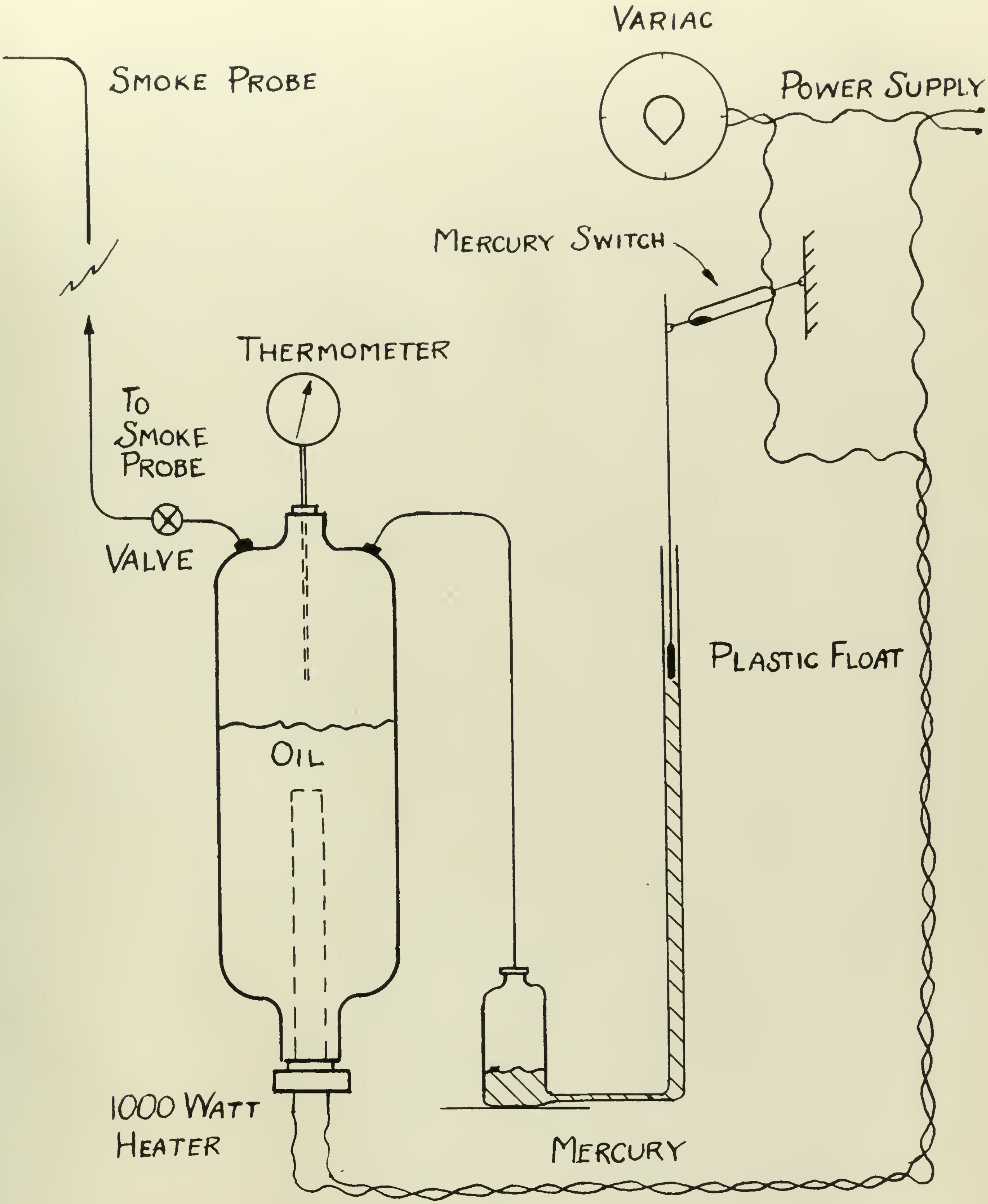


Fig 1-A
Schematic Diagram of
Smoke Generating Equipment

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